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RESEARCH MEMORANDUM FOR REFERENCE

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INVESTIGATION OF MECHANISMS OF BLADE FAILURE OF
FORGED HASTELLOY B AND CAST STELLITE 21

TURBINE BLADES IN TURBOJET ENGINE

By C. Yaker, C. F. Robards, and F. B. Garrett

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Cleveland, Ohio
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INVESTIGATION OF MECHANISMS OF BLADE FAILURE OF

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- SUMMARY

An investigation was conducted to determine the mechanisms of failure of turbine blades of Hastelloy B, a forged nickel-base alloy, and Stellite 21, a precision-cast cobalt-base alloy, when operated in a J33-9 turbojet engine. The blades were alternately spaced in a 16-25-6 alloy rotor and subjected to simulated service operation consisting of 20-minute cycles (15 min at rated speed and approximately 5 min at idle). The engine conditions at rated speed were 11,500 rpm and a gas temperature of 1250° F at the exhaust-cone outlet. For these operating conditions, the estimated maximum blade temperature in the normal zone of failure was 1500° F and the centrifugal stress in this zone was 25,000 pounds per square inch for the Hastelloy B and 21,000 pounds per square inch for the Stellite 21 blades.

The results of stress-rupture tests on specimens cut from blades indicated that the minimum blade life at rated speed should be 10.3 hours for Hastelloy B and 21 hours for Stellite 21. The first Hastelloy B blade failed after 14.25 hours (57 cycles) at rated speed; the first Stellite 21 blade failed after 16.75 hours (67 cycles). Both of these failures originated at the trailing edges of the blades and were probably the result of excessive vibratory stresses. Inter-crystalline cracking of the stress-rupture type was detected in both alloys after 16.75 hours (67 cycles) of operation. Additional failures of Hastelloy B blades occurred after 18.47 hours (< 74 cycles) and 28.75 hours (115 cycles) at rated speed as a result of the propagation of the previously formed intercrystalline cracks. These failures progressed by both fatigue and stress-rupture mechanisms. After 28.75 hours of operation, all but three of the original 27 Hastelloy B blades had either failed or contained stress-rupture-type cracks. No additional Stellite 21 failures occurred up to 28.75 hours (115 cycles) at rated conditions except two blades fractured by impact

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with the fractured half of a Hastelloy B blade. After 28.75 hours of operation, stress-rupture-type cracks had formed in four of the original Stellite 21 blades.

INTRODUCTION

One of the principal factors limiting the performance time of gas turbines used in current jet engines is the operating life of the turbine blades. Improvement of blade life is therefore one of the primary objectives of current gas-turbine research. Laboratory evaluations of heat-resistant alloys have established such elevated-temperature properties as stress rupture, creep, and fatigue strength with the realization that one or a combination of all these properties may define the life of a turbine blade. Before an alloy can be selected for use as a blade material, however, a determination of the relative importance of its various physical properties in defining blade life is necessary.

Engine operation of a turbine blade can result in the following types of failure:

- (1) Creep-rupture failure, resulting from centrifugal stress and temperatures
 - (a) Creep failure, blade elongation in excess of defined limits
 - (b) Stress-rupture failure, blade fracture before elongation exceeds defined limits
- (2) Fatigue failure, blade fracture due to alternating stresses
- (3) Thermal-shock failure, blade fracture due to thermal stresses resulting from temperature gradients

Failures can also result from the combined effects of several mechanisms, for example, a fatigue failure originating at a crack produced by thermal stresses. Another type of failure is that resulting from damage produced by other blade failures or failure of other engine components. Because these failures occur as the result of extraordinary conditions, they will not be considered in evaluating the performance of the blades.

A comparison of the results of blade performance in a gas turbine with existing data from standard laboratory tests, when combined with a determination of the mechanisms of blade failure, should yield a basis for predicting blade life from the known high-temperature properties of an alloy.

As part of the over-all program to investigate heat-resistant alloys for use in turbojet engines, an investigation was conducted at the NACA Lewis laboratory to determine the high-temperature properties that define the turbine-blade life of a forged nickel-base alloy, Hastelloy B, and a precision case cobalt-base alloy, Stellite 21. The blades were alternately mounted in a 16-25-6 alloy rotor and operated under cyclic (simulated service) conditions in a J33-9 turbojet engine. At intervals during the engine operation, the turbine blades were measured to determine the amount of blade creep and inspected for evidence of failure or damage. Simultaneously with the engine operation high-temperature stress-to-rupture tests were conducted of specimens cut from the airfoil section of blades of each alloy to allow a comparison of the stress-rupture life of the blade with engine life. At the conclusion of operation, all blade and stress-rupture specimen failures were examined metallurgically to determine the nature of the origin of failure and the mechanism of failure propagation.

APPARATUS AND PROCEDURE

Turbine Blades

Fabrication history. -

Nominal chemical composition	Stellite 21 (reference 1)				Hastelloy B (manufacturer's data)			
	C	Cr	Mo	Ni	C	Mo	Fe	Ni
	0.20- .35	25.00- 29.00	5.00- 6.00	1.75- 3.75	0.12 max.	26.0- 30.0	4.0- 7.0	Remain- der
	Mn	Si	Fe	Co				
	1.00 max.	1.00 max.	2.00 max.	Remain- der				
Fabrication	Precision cast				Forged			
Heat treatment	None				2 hr at 1900° F, air-cooled 4 hr at 1500° F, air-cooled			

Preinstallation inspection. -

Radiographic	All blades without flaws
Optical comparator	Cross-sectional areas of several blades measured; stress distributions calculated by method described in reference 2

Installation (fig. 1). -

Rotor	16-25-6 alloy
Total number of blades	54
Blade positions	Alternated, with Stellite 21 blades odd numbered and Hastelloy B blades even numbered

Engine Operation

Engine. - (Engine, fuel, and engine instrumentation described in reference 3)

Type	Turbojet
Designation	J33-9
Nominal thrust	4000 lb
Compressor	Dual-entry centrifugal
Combustion chambers	14

Operating cycle^a. -

Duration		Rotor speed (rpm)	Gas temperature at exhaust-cone outlet (°F)
(min)	(sec)		
4	30	4000 ± 50	1110 max.
0	15	Acceleration to 11,500	1450 ± 50
15	0	11,500 ± 50	1250 ± 20
0	15	Deceleration to 4000	1260 max.

^aCyclic operation was employed during this investigation to simulate the starting and shutdown conditions encountered in service.

Observations between engine operations. -

Measurement of blade and wheel elongation	Optical extensometer readings of an accuracy of ± 0.0001 in. between gage marks on two blades of each alloy and on the turbine wheel (see fig. 2)
Location and detection of blade cracks	Visual examination during engine shutdown and overhaul

Blade Specimen Stress-Rupture Tests

Loading system	Simple beam acting through system of knife edges
Furnace	Resistance type
Temperature control	Less than 5° F variation along specimen; average temperature variation $\pm 2^{\circ}$ F
Specimens	Cut from center of blade airfoil section (see fig. 3)
Test conditions	Stress and temperature same as estimated at midpoint of blade during engine operation

Blade Examination after Testing

Determination of reduction in area of a blade of each alloy	Optical comparator
Examination of surface condition and fractures	Low-power microscope
Location of blade cracks	Fluorescent-oil examination
Hardness distribution along blades	Rockwell hardness tester
Microexamination of blade and stress-rupture specimen failures	Standard metallurgical equipment and procedures

RESULTS

Blade Stress Calculations

The results of the stress determinations based on the measured cross-sectional areas and 11,500 rpm for the two alloys Hastelloy B and Stellite 21 are plotted in figure 4. The stress curves are based on the average areas of six blades and an engine speed of 11,500 rpm.

Stress-Rupture Tests

The results of the rupture tests on the individual Hastelloy B and Stellite 21 specimens cut from blades are listed in table I. Microscopic examination of broken stress-rupture specimens indicated that the stress-rupture fractures were intercrystalline in both alloys (figs. 5 and 6).

Engine Operation

The results of engine operation and the blade examination after testing are listed chronologically in table II and the types of failure encountered are shown in figures 7 to 14.

Blade Elongation

The results of the elongation measurements on the blades are presented in figure 15. Figure 16 shows the time-elongation curves for the entire blades and for the gage sections with a total elongation at the conclusion of test of greater than 1 percent. There was no measureable elongation in the 16-25-6 alloy turbine rotor.

Blade Reduction in Area

The results of the reduction in area measurements of a Hastelloy B blade after 28.75 hours (115 cycles) of operation are shown in figure 17. These results are only qualitative inasmuch as they represent the change in area of a single blade compared with the average area of the Hastelloy B blades prior to operation. The measurements of the area of a Stellite 21 blade after operation did not indicate any measureable reduction in area.

Surface Condition and Oxide Coloring of

Blades and Blade Fractures

The Stellite 21 blade surfaces after 28.75 hours (115 cycles) of operation were coated with a thin dark-gray oxide and exhibited the "alligator skin" appearance characteristic of deformation in coarse-grained alloys, as described in reference 4. (See fig. 18.) The Hastelloy B blade surfaces were coated with a flaked dark-brown-to-purple oxide and exhibited a slight amount of oxide pitting. The fracture surfaces of all Hastelloy B blades were coated with a similar oxide pattern, a dark-gray oxide at the fracture origin that changed to a blue temper color as the fracture progressed across the blade. This same color pattern also existed on the fracture surface of Stellite 21 blade 25. The colorings of the fracture surfaces of Stellite 21 blades 1 and 3, however, were anomalous in that they were entirely a straw temper color.

Hardness Distribution along Blades after Operation

Typical hardness-distribution curves are shown in figures 19 and 20 for the Hastelloy B and Stellite 21 turbine blades, respectively, after 28.75 hours (115 cycles) of operation. Each point on these plots represents an average of three to five Rockwell-A hardness values. The hardness distributions in the blades that failed were generally the same as those in figure 19. These plots indicate that the maximum hardness occurs around the center of the airfoil section of the blades.

The hardness of as-received blades of these alloys ranged from a Rockwell-A of 63 to 65 for Stellite 21 and 55 to 57 for Hastelloy B. Manufacturer's data on these alloys indicate that age hardening occurs at 1500° F (the maximum blade temperature in the engine) and that the hardness changes observed at the point of maximum hardness are of the order of magnitude that would be expected for the times the blades were in operation.

DISCUSSION OF RESULTS

Blade Stress and Temperature

Before a complete analysis of the results of this investigation can be made the stress and temperature conditions to which the blades are subjected in the engine must be established. Earlier investigations of temperature distributions in turbine blades (reference 5) indicate that the maximum blade temperature occurs about at the middle

zone of the airfoil section of the blade or about 2 inches from the top of the blade root. Although no temperature distributions are available for the gas temperatures used in this investigation, measurements at this laboratory of the maximum blade temperature at rated speed indicate that for an average gas temperature of 1250° F (measured at the exhaust-cone outlet) the maximum blade temperature ranges from 1450° to 1500° F depending on the operating characteristics of the engine. The zone of maximum temperature is generally the failure zone of the blades in this engine. From the average stress distributions at rated speed for these alloys (fig. 4), the centrifugal stress at the midpoint of the airfoil section of the Hastelloy B blades is established at 25,000 pounds per square inch and the Stellite 21 blades at 21,000 pounds per square inch. These stresses have been selected as the critical stresses in the blades because they occur at the estimated zone of blade failure and the point of maximum blade temperature. At the midpoint of the blade during operation, therefore, the combined average stress and maximum temperature are 25,000 pounds per square inch and 1500° F for Hastelloy B and 21,000 pounds per square inch and 1500° F for Stellite 21.

Comparison of Laboratory and Engine Tests

The results of the stress-rupture and engine tests of the Hastelloy B and Stellite 21 blades are compared with available strength data for these alloys in figure 20. All the blade failures are plotted on this curve, although some of the failures apparently were not of the stress-rupture type, to determine if stress rupture might have contributed to initiating failure even though metallurgical examination revealed no evidence of stress-rupture cracks. The design stress-rupture data of the manufacturer for Hastelloy B at 1500° F, although a heat treatment different from that of this investigation was used, compare favorably with the results of the rupture tests on specimens cut from blades. At a stress of 25,000 pounds per square inch, the manufacturer's data indicate a rupture life of 12 hours; the blade specimens had rupture lives ranging from 10.3 to 19.2 hours, or within the range that might be expected from the manufacturer's data. In the case of the alloy Stellite 21, the results of the blade-specimen rupture tests fall within the stress-rupture band for the alloy. For a maximum blade temperature of 1500° F, the minimum rupture life of the Hastelloy B blades at the average stress of 25,000 pounds per square inch would be 10.3 hours, the minimum rupture life of Stellite 21 blades at the average stress of 21,000 pounds per square inch would be 21 hours (minimum predicted by stress-rupture band).

From the results of the engine operation, the first Hastelloy B blade failure occurred in the trailing edge of blade 14 after 14.25 hours of operation or within the range predicted by the stress-

rupture tests (fig. 20). This failure, however, could not be classed as a stress-rupture failure because unlike a rupture failure, it was transcrystalline in its propagation and had a smooth fracture surface. The failure started at a point on the blade above the zone of critical stress and maximum temperature (fig. 7). From the nature of the fracture, therefore, vibratory stresses were probably a principal cause of this first failure. After 16.75 hours of operation, the majority of the remaining Hastelloy B blades developed intercrystalline leading-edge cracks characteristic of the stress-rupture failures of the blade specimens. Inasmuch as this operating time was within the stress-rupture failure times expected from operating conditions, these cracks can be considered as evidence of the beginning of blade failure by stress rupture. The distribution of these cracks along the leading edge (fig. 11(a)) suggests that corrosion or localized hot zone along the leading edge may have been partly responsible for their formation. However, the correlation of the nature of the crack propagation and the time of the crack formation with the results of the stress-rupture tests on blade specimens indicates that other contributing causes such as corrosion are of less importance. As the engine operation continued, the remaining Hastelloy B blade fractures progressed from these leading-edge cracks. The failures progressed by two mechanisms, fatigue and stress rupture. Hastelloy B blades 4 and 34 (figs. 11(b) and 11(d)) fractured after 18.47 hours of (1.72 additional hr) operation as a result of a condition favorable for fatigue fracture having been set up by the leading-edge cracks. The vibratory stresses in the blades were therefore merely propagating a failure originated by stress rupture. In Hastelloy B blade 54 after 28.75 hours (12 additional hr) of operation, fracture occurred by the progression of the initial crack across the blade continued by a stress rupture following an intercrystalline path. Some of the original Hastelloy B blades were still in operation at times in excess of the predicted rupture life, which would be expected since a complete stress-rupture band for the alloy was unavailable, making the maximum blade life unknown. All but three of the original 27 Hastelloy B blades, however, had cracked or fractured at the conclusion of operation, indicating that failure had started in all but three blades.

In the case of the Stellite 21 blades, the first blade failure (blade 25) occurred after 16.75 hours, which is below the predicted rupture life of 21 hours. Like the first Hastelloy B failure, the fracture started at the trailing edge and was not of the characteristic stress-rupture type inasmuch as it was transcrystalline in its propagation and had smooth fracture facets. Also like the first Hastelloy B failure, fracture started at a point above the zone of critical stress and maximum temperature. As in the case of the first Hastelloy B blade, therefore, vibratory stresses were largely responsible for this fracture. At this same time (16.75 hr), intercrystalline

cracking was detected in two Stellite 21 blades. The nature of this cracking is characteristic of the beginning of failure by stress rupture. Because the first cracked Stellite 21 blades were removed from the engine, their exact life cannot be determined. However, because seven of ten cracked Hastelloy B blades left in the engine at the same time operated for 12 additional hours without failure, the cracked Stellite 21 blades would probably have operated for the length of time predicted by the rupture band before failing. At the conclusion of operation, Stellite 21 blades 1 and 3 were fractured. Inasmuch as blades 1 and 3 were close to the fractured blade 54 (fig. 14), failure was probably caused by impact with the upper half of the fractured blade. This mechanism of failure is corroborated by the following facts: (1) The fracture surfaces were not of the stress-rupture or fatigue type, and (2) the fracture surfaces were covered completely with a light straw color indicating that the entire fracture occurred at the same time and that the surfaces were exposed for only a very short time. Because these failures are the result of extraordinary causes, they will not be considered in evaluating the performance of alloy Stellite 21. The only additional evidence of failure in Stellite 21 at the conclusion of operation were the two additional blades that had formed intergranular cracks of the stress-rupture type after 28.75 hours of operation.

Blade Creep

The creep characteristics of the alloys during engine operation can be determined by examining the elongation curves in figure 15. In the case of the Hastelloy B blades, when cracking started at 16.75 hours the two blades that were measured had an elongation in the gage section of greatest stretch of 5 percent. One measured blade, Hastelloy B blade 54 (fig. 16(b)), shows some evidence of third-stage creep at 16.75 hours but this change in the curve may be not significant inasmuch as the same effect in blade 40 (fig. 16(a)) did not continue with further operation. After 28.75 hours of operation, blade 40, the other measured blade, had a maximum elongation of 8 percent. Blade 54 fractured so that no final elongation data could be determined. Unfortunately no data were available in the literature for Hastelloy B to check with the data for creep characteristics in the engine. The zone of maximum elongation varied in the two scribed blades; in blade 54 it was gage section 3 (from $1\frac{3}{8}$ to $1\frac{7}{8}$ in. from the top of the root) and in blade 40 it was gage section 4 (from $1\frac{7}{8}$ to $2\frac{3}{8}$ in. from the top of the root). These differences are probably the result of

dimensional differences between the blades that produced different stress distributions. The results of the blade-hardness and reduction-in-area measurements of the Hastelloy B blades both indicate that the elongation measurements are fairly reliable in defining the zone of maximum stress and temperature effect in the blades.

In the case of the Stellite 21 blades (figs. 16(c) and 16(d)), at the time that first cracks were noted (after 16.75 hr of operation) maximum elongations of around 2 percent existed in gage section 4 on the blades. This gage section, which is from $1\frac{7}{8}$ to $2\frac{3}{8}$ inches from the top of the blade root, exhibited the highest elongation in both scribed blades. The curves in figures 16(c) and 16(d) also show a slight change in slope at about 2-percent elongation. Because first cracks were also noted at 16.75 hours, this time probably marks the initiation of third-stage creep. Although the sensitivity of the method of creep measurement is probably not high enough to make this change in slope of the time-elongation curves significant, the results are somewhat confirmed by the work of other investigators. The data in reference 7 indicate that Stellite 21 when rupture-tested at a temperature of 1500°F and a stress of 20,000 pounds per square inch will enter third-stage creep at elongations of about 2 to 3 percent. The time-elongation curves for both the Stellite 21 and Hastelloy B blades also illustrate the unreliability of total blade-elongation measurements as a means of predicting the creep characteristics of an alloy during service operation. The results plotted in figure 16 indicate that the percentage elongation in localized zones in the blade can be one to three times the percentage elongation of the entire blade.

Prediction of Blade Life

The results of the blade-operation and blade-elongation measurements indicate that the engine life of alloys Stellite 21 and Hastelloy B as turbine blades in the engine used in this investigation can be defined to some extent by their creep and rupture properties. Although the number of fractured blades of each sample was small both alloys had a number of cracked blades. In the case of the shorter-lived Hastelloy B blades, 88 percent of the blades were either fractured or cracked. In the case of the longer-lived Stellite 21 blades, 15 percent of the blades were cracked. These first cracks serve as the probable nuclei of fatigue failures and although the rupture life of the alloy extends beyond this point the probability of failure has been greatly increased by these cracks and further operation of these blades is undesirable. The defining point in the life of these blades was therefore the time of initiation of stress-rupture cracks. The initiating of this first cracking

is probably very closely associated with the beginning of third-stage creep in the blades. The limited number of failures and the fact that the elongation of only two blades of each alloy was determined prevent a more exact prediction of the relation between creep, stress-rupture properties, and blade life. It should be noted that the first failures of both the Stellite 21 and Hastelloy B blades were anomalous in the sense that they were not of the stress-rupture type, although the Hastelloy B blade did fail within the time predicted by stress-rupture tests. The similarity of these two failures is apparently significant. Both were probably the result of vibratory stresses superimposed on the centrifugal stresses. These blades represented only 3.7 percent of each blade sample, however, and therefore were not characteristic of all blades of the alloys. Any of the following factors could have caused these blades to become susceptible to vibratory-stress failure: (1) flaws in blades not detectable by regular inspection; (2) undetectable surface damage; and (3) unusual vibratory stresses. The cause of these failures should be determined so that they can be eliminated to allow alloys to perform as turbine blades to their full life as predicted by their elevated-temperature stress-rupture and creep properties.

It should be emphasized that the results of this investigation were obtained in a specific turbojet engine. With changes in the design of this engine, or in other types of engine, operating conditions may produce different results so that a prediction of material blade life may depend on properties other than those determined in this investigation.

SUMMARY OF RESULTS

The following results were obtained from a cyclic evaluation of the alloys Stellite 21 and Hastelloy B as turbine blades in a J33-9 engine at a rotor speed of 11,500 rpm and a gas temperature at the exhaust-cone outlet of 1250° F. For these operating conditions, the estimated conditions in the zone of blade failure were a maximum temperature of 1500° F and a stress of 25,000 pounds per square inch for the Hastelloy B blades and a stress of 21,000 pounds per square inch for the Stellite 21 blades.

1. The expected minimum life of the turbine blades at the conditions in the zone of blade failure on the basis of stress-rupture tests on specimens cut from turbine blades was 10.3 hours for Hastelloy B and 21 hours for Stellite 21.

2. The first blade failure of the Hastelloy B blades occurred after 14.25 hours (57 cycles). The first Stellite 21 blade failure occurred after 16.75 hours (67 cycles) of operation. Both failures started at the trailing edges above the zone of maximum temperature and high stress and were probably the result of excessive vibratory stresses.

3. Intercrystalline cracking of the stress-rupture type was detected in both alloys after 16.75 hours (67 cycles).

4. Additional failures occurred in Hastelloy B blades after 18.47 hours (<74 cycles) and 28.75 hours (115 cycles). These resulted from the propagation of the previously formed intercrystalline cracks by both fatigue and stress-rupture mechanism. At the conclusion of 28.75 hours of operation, 24 of the original 27 Hastelloy B blades, which had not failed, had stress-rupture-type cracks.

5. No additional Stellite 21 failures occurred up to 28.75 hours (115 cycles) except two blades that were fractured by impact with the fractured half of a Hastelloy B blade. At the conclusion of 28.75 hours of operation, four of the original 27 Stellite 21 blades had stress-rupture-type cracks.

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TABLE I - STRESS-RUPTURE LIFE OF BLADE SPECIMENS
AT TEMPERATURE OF 1500° F

Stress (lb/sq in.)	Rupture life (hr)	
	Hastelloy B	Stellite 21
20,000	----	55.0
20,000	----	43.0
20,000	----	55.0
20,000	----	38.2
22,000	----	35.0
22,000	----	19.3
22,000	----	20.4
22,000	----	21.3
30,000	----	12.0
30,000	----	6.0
25,000	15.4	----
25,000	12.1	----
25,000	10.3	----
25,000	18.4	----
25,000	19.2	----



TABLE II - RESULTS OF ENGINE OPERATION AND POST-OPERATION INSPECTION OF HASTELLOY B AND STELLITE 21

Alloy	Blade	Time at rated speed (hr)	Origin of failure	Turbine blades		Apparent cause of failure
				Description of failure surface	Failure propagation	
Hastelloy B	14 ^c	14.25	Trailing-edge crack	Partly smooth and partly rough appearance (see fig. 7)	Transcrystalline (fig. 8)	Vibratory stresses superimposed on centrifugal stress (fatigue)
Stellite 21	25 ^d	16.75	Trailing-edge fracture	Fracture path at angle to horizontal. Fracture started with zone with smooth crystalline facets then changed to zone of rough surface (fig. 9(a))	Transcrystalline (fig. 10)	Vibratory stresses superimposed on centrifugal stress (fatigue)
Hastelloy B	4 6 8 ^a 10 ^c 12 ^c 15 ^c 18 ^c 20 ^c 22 ^c 30 ^c 32 ^c 34 ^c 36 ^c 38 ^c 46 ^c 48 ^c 50 ^c 52 ^c 54 ^c	16.75	Leading-edge cracks (for example, fig. 11(a))		Interocrystalline (fig. 12)	Centrifugal stress (stress rupture)
Stellite 21	17 ^c 21 ^c	16.75	Center cracks (away from edges)		Interocrystalline	Centrifugal stress (stress rupture)
Hastelloy B	4 ^c	16.47	Leading-edge fracture	Fracture started normal to edge from point where crack was observed then changed direction and moved at angle with horizontal. The surface in flat portion of fracture has concentric-ring markings typical of fatigue failure. The remaining surface has coarse appearance (figs. 11(b) and 11(c)).	Interocrystalline changing to transcrystalline (fig. 13)	Centrifugal stress at origin, fracture then propagated to vibratory stresses (stress rupture to fatigue)
Hastelloy B	34 ^c	16.47	Extension of leading-edge crack (crack only)	Same as start of fracture in blade 4 (fig. 11(d))	Interocrystalline changing to transcrystalline (fig. 13)	Same as preceding blade 4
Hastelloy B	54 ^c	26.75 ^e	Leading-edge fracture	Fracture path at angle to horizontal from point where crack was observed. Entire surface has coarse appearance (fig. 11(e)).	Interocrystalline	Centrifugal stress (stress rupture)
Hastelloy B	2 24 26 28	26.75	Leading-edge cracks		Interocrystalline (fig. 12)	Centrifugal stress (stress rupture)
Stellite 21	1 3	26.75	Fracture origin not determinable	Irregular fracture surface having coarse appearance (figs. 9(b) and 9(c))	Transcrystalline	Impact with failure fragments suggested by close proximity of failures as shown in fig. 14
Stellite 21	33 45	26.75	Center cracks (away from edges)		Interocrystalline	Centrifugal stress (stress rupture)

^aBased on results of prefailure inspection and oxide coloring.^bBased on failure propagation in stress-rupture tests and appearance of fracture surface.^cBlade replaced with new blade.^dFailures at points of previously noted cracks.^eTest was concluded at this time because of severe damage to remaining blades in rotor.

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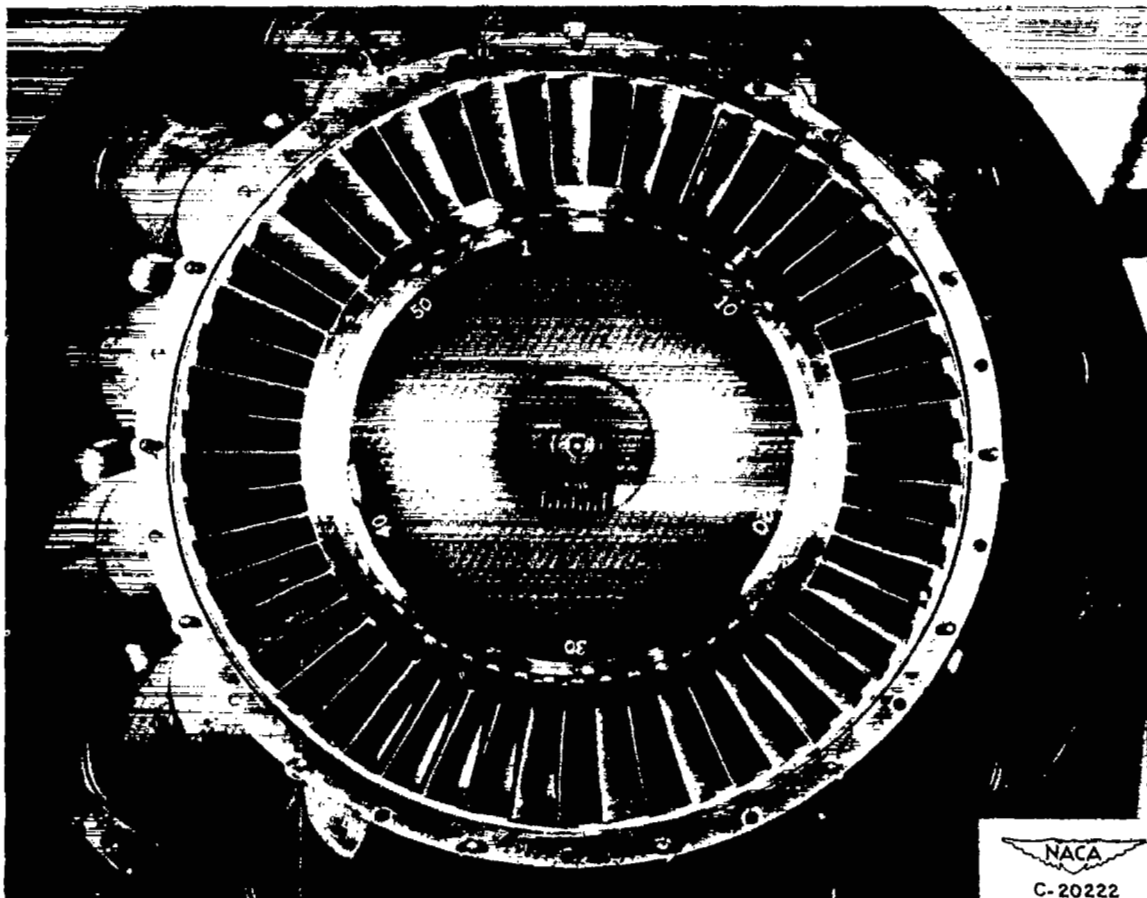


Figure 1. - Turbine rotor of Timken alloy before operation, alternately bladed with Hastelloy B and Stellite 21 turbine blades.

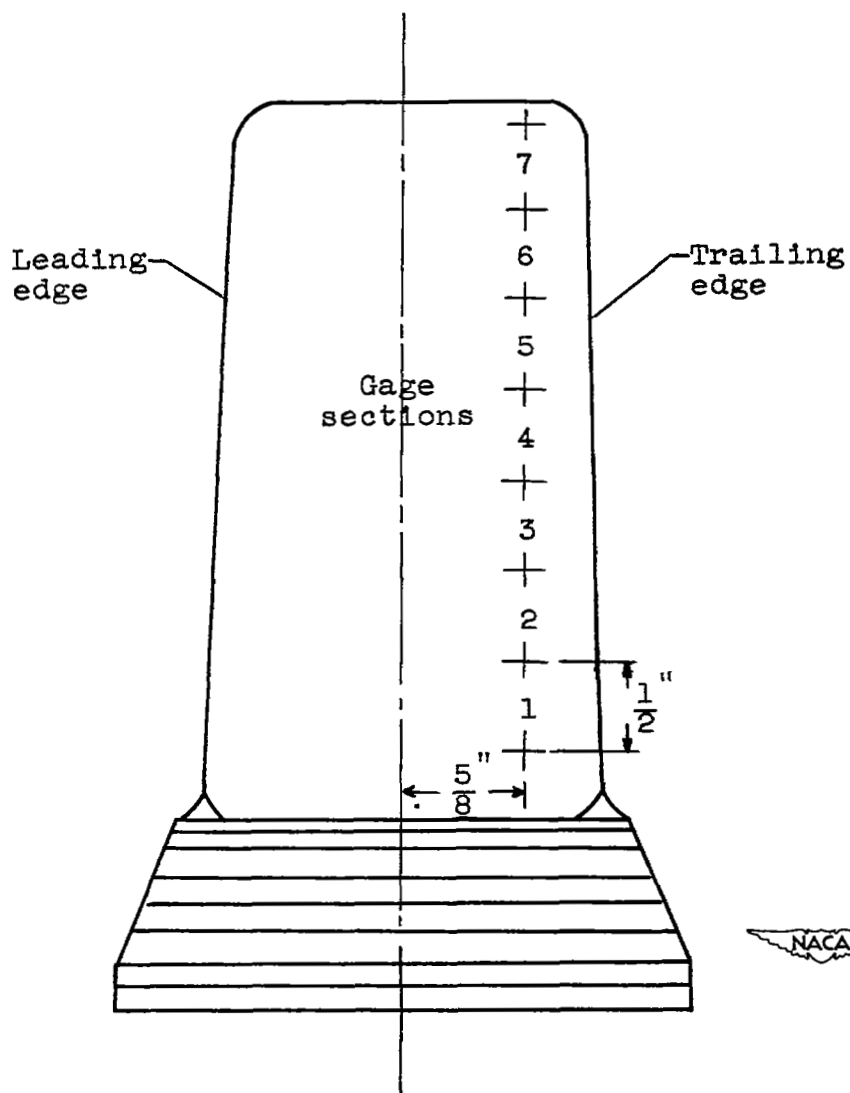


Figure 2. - Location of scribe marks on convex side of turbine blade for measurement of elongation.

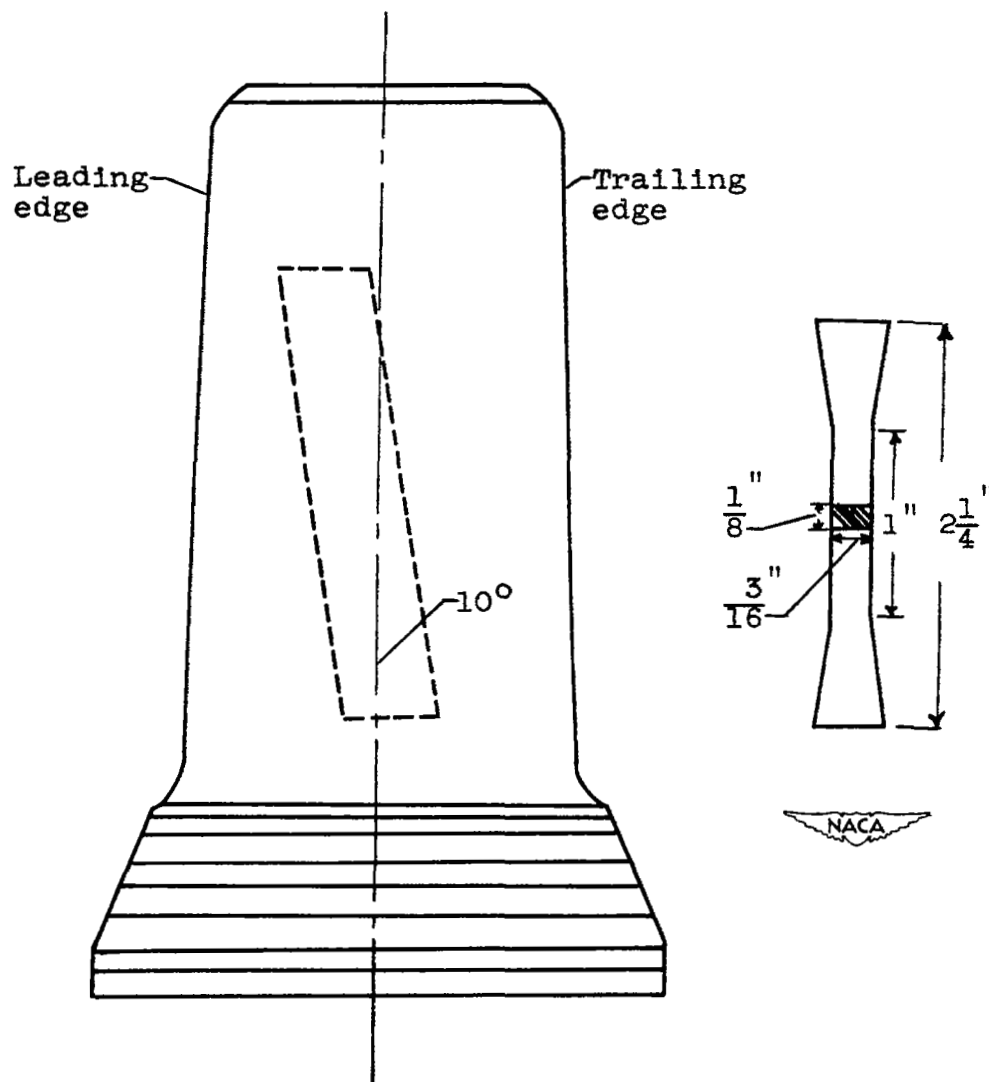


Figure 3. - Blade stress-rupture specimen and zone from which specimen is machined.

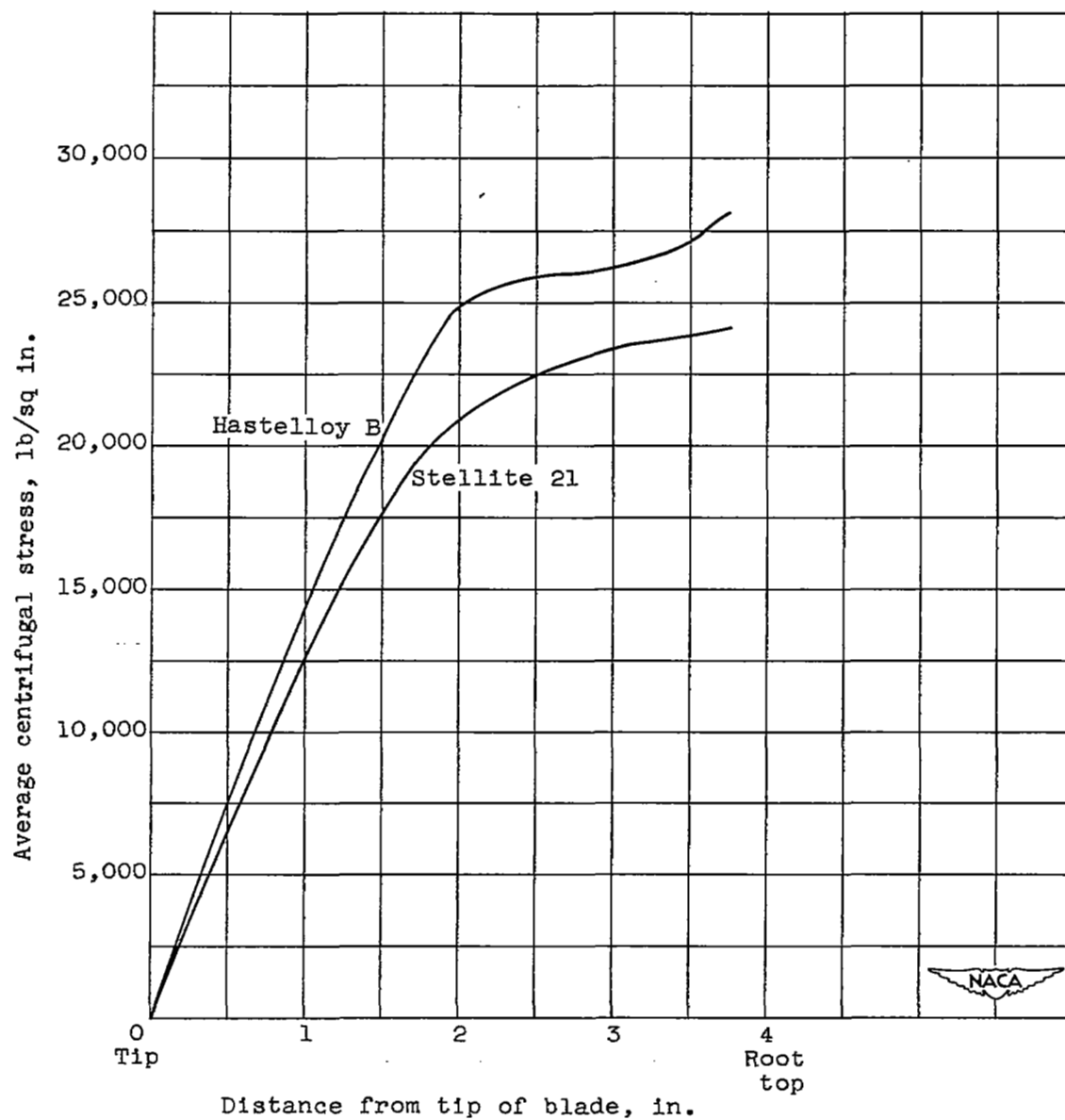


Figure 4. - Average centrifugal stress distributions in Hastelloy B and Stellite 21 turbine blades at rotor speed of 11,500 rpm.

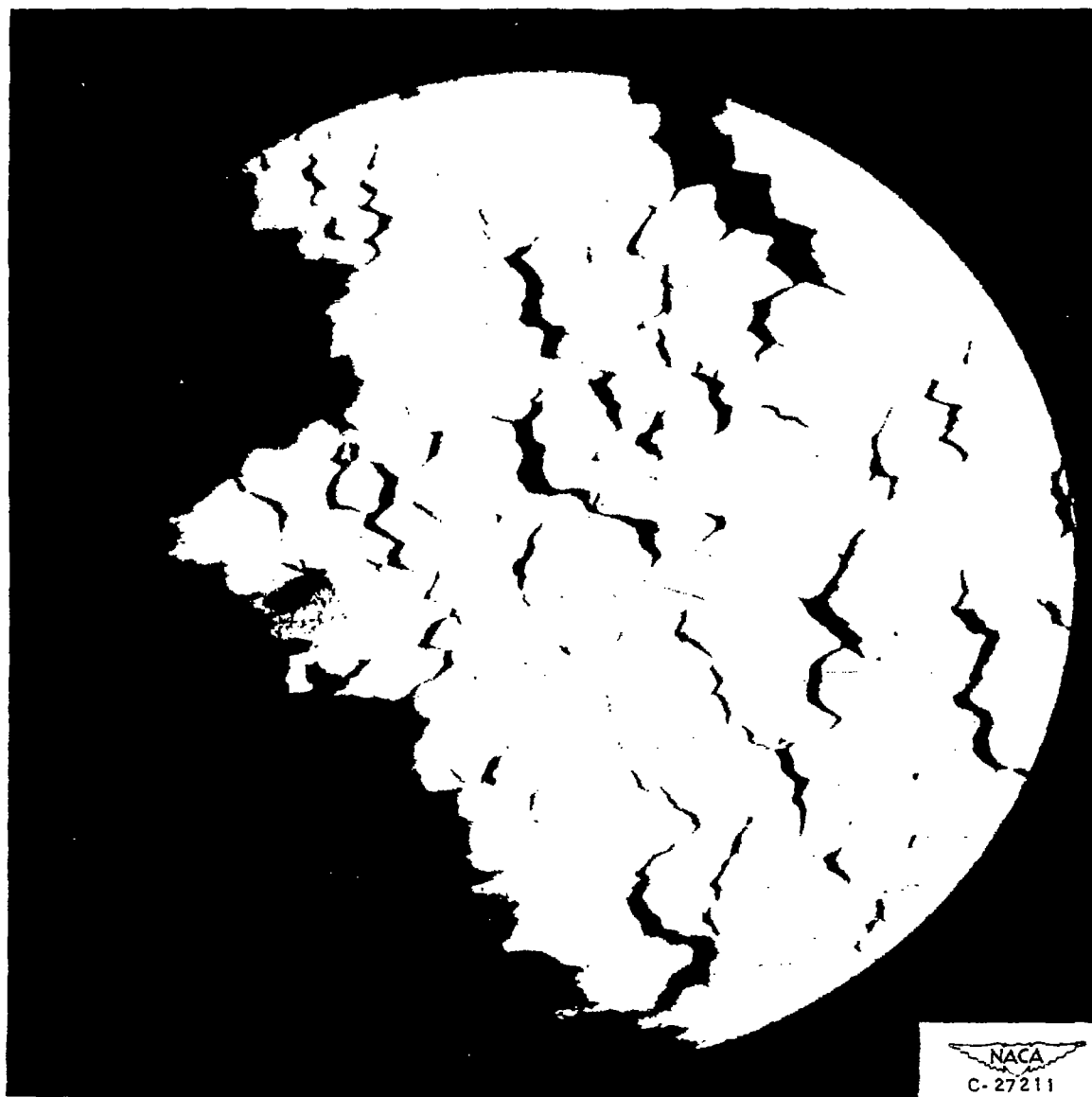


Figure 5. - Intercrystalline fracture in Hastelloy B stress-rupture specimen. Etched in solution of aqua regia in glycerine. X50.

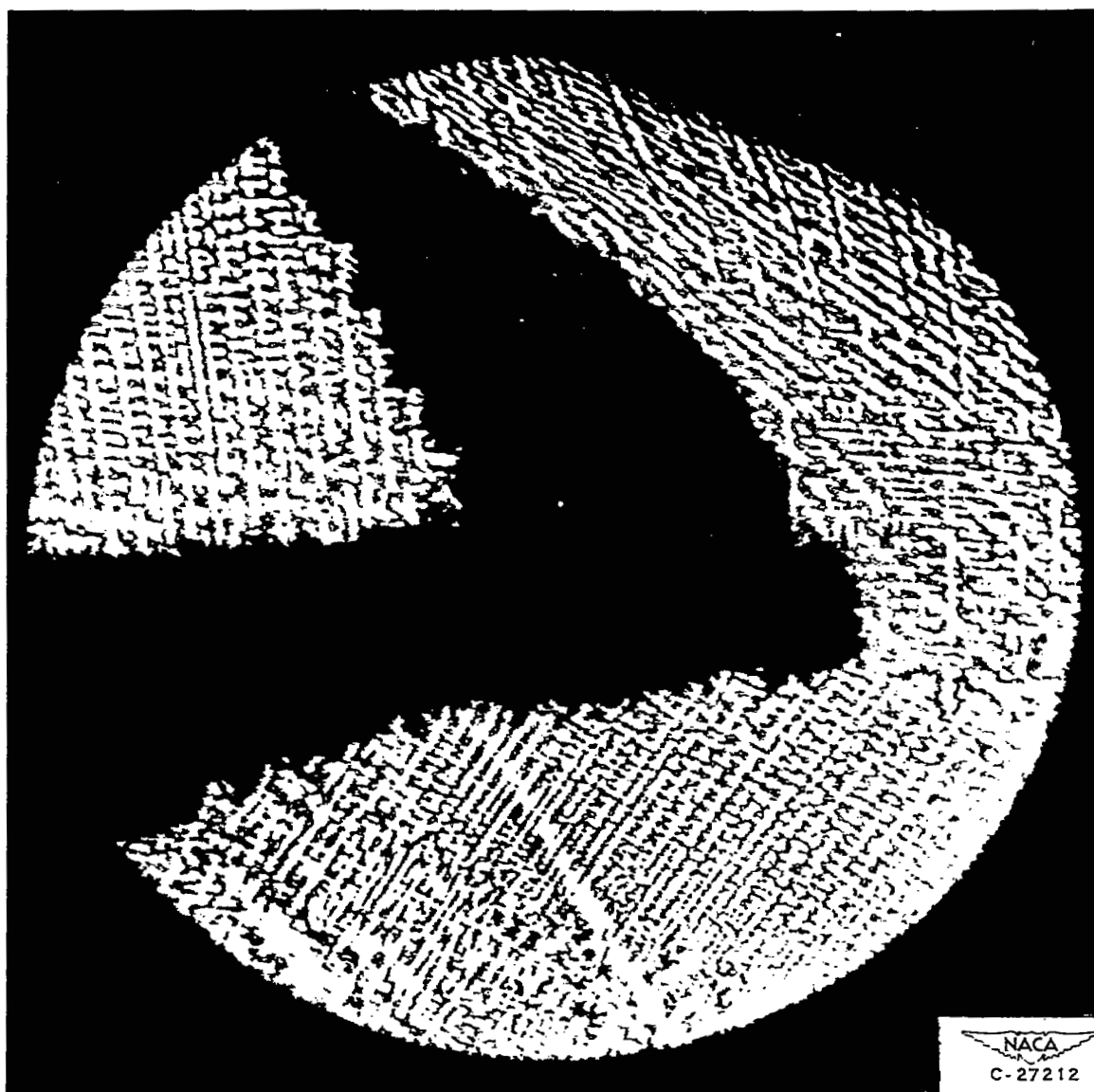


Figure 6. - Intercrystalline fracture in Stellite 21 stress-rupture specimen. Electrolytically etched in solution of 10-percent nitric acid and 10-percent ethylene glycol in ethyl alcohol. X50.

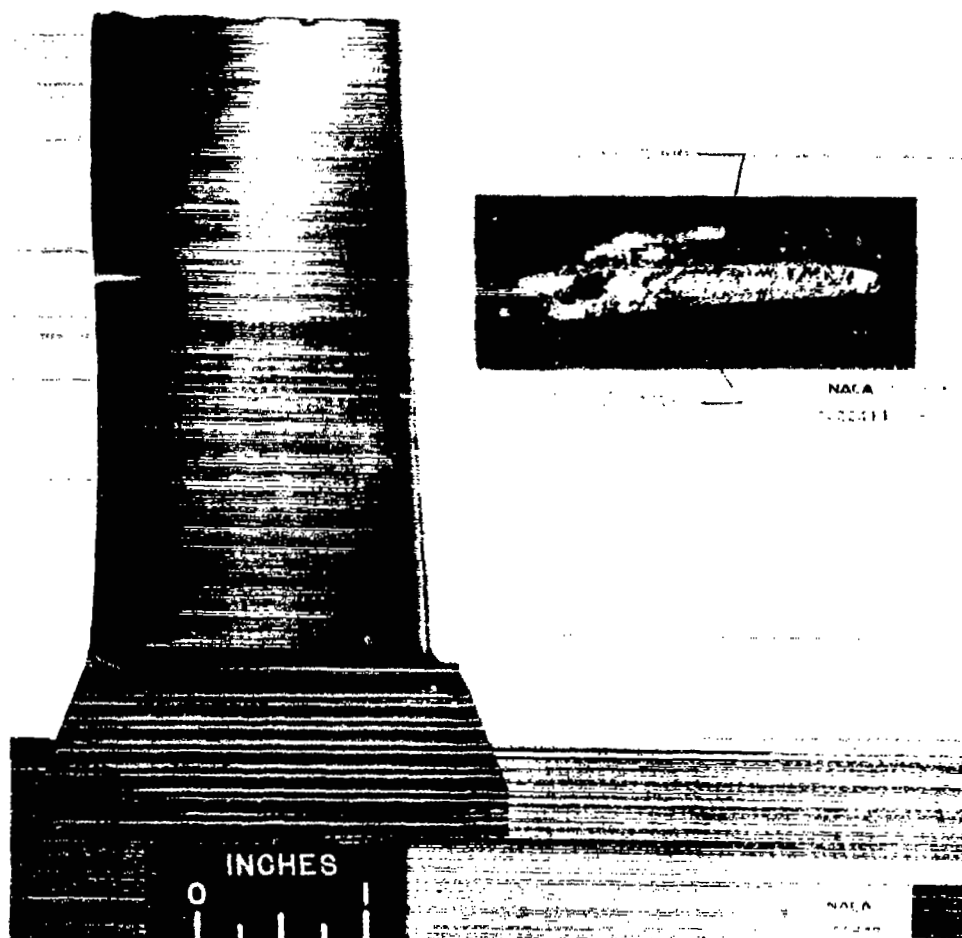


Figure 7. - Trailing-edge crack in Hastelloy B blade 14 after 14.25 hours (57 cycles) of operation. (Fracture surface of crack at X5 shown in inset.)

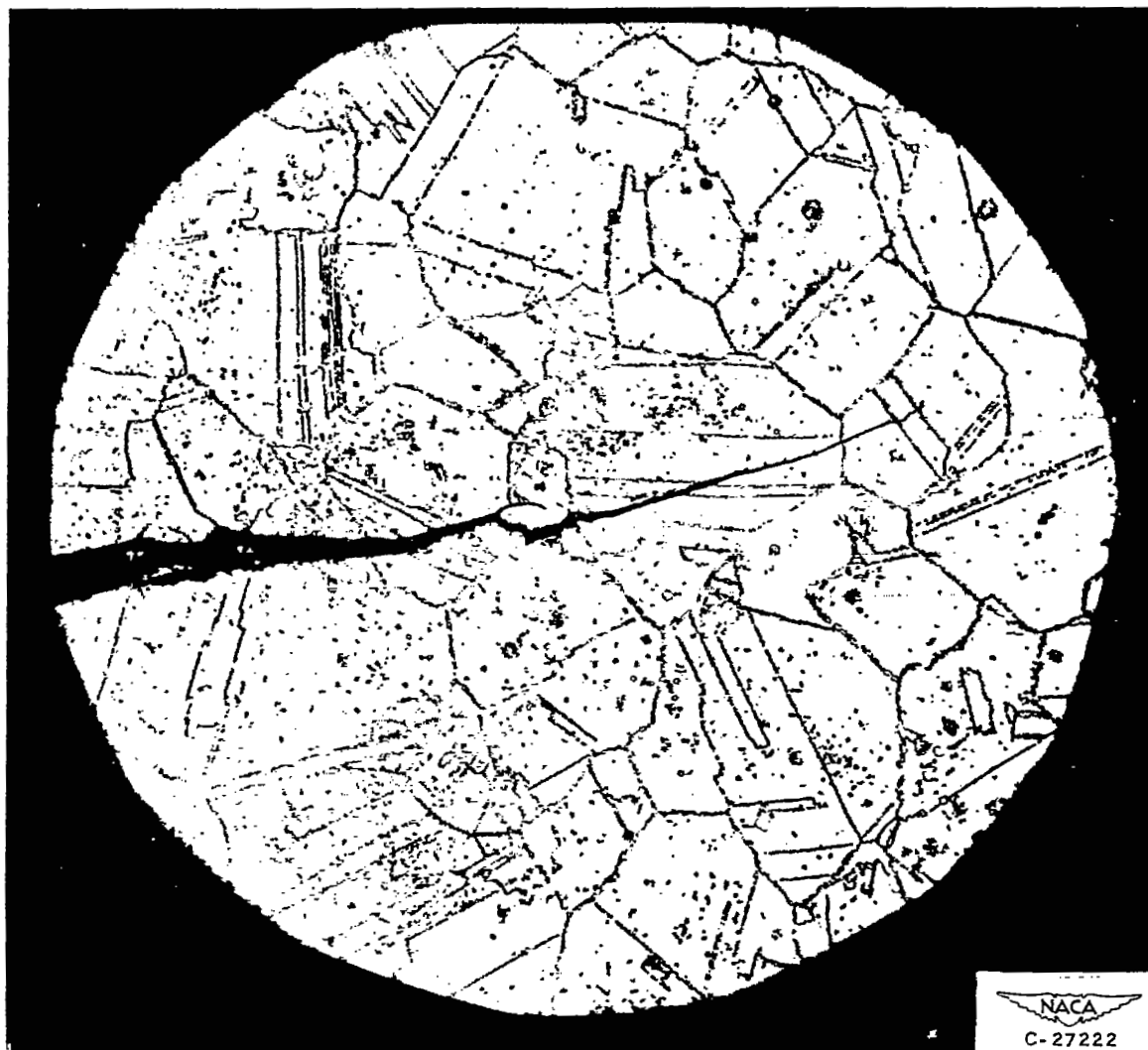
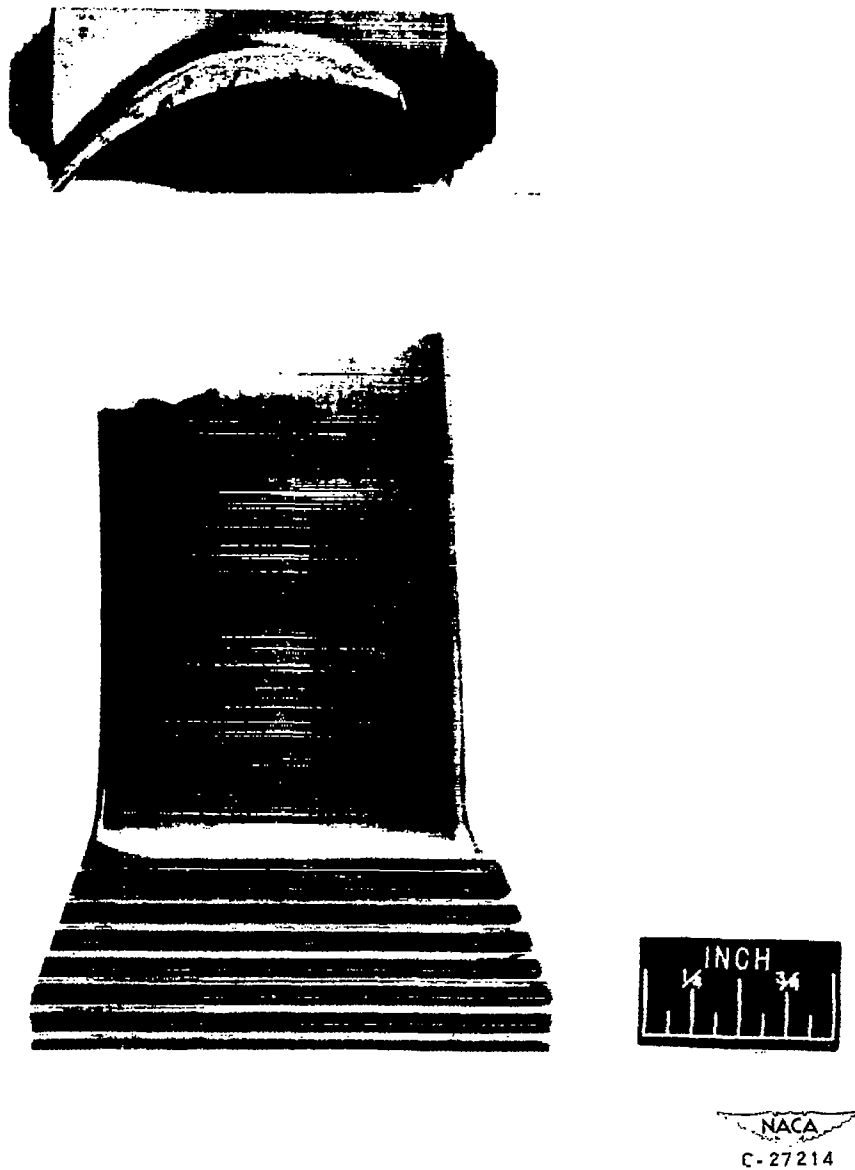


Figure 8. - Transcrystalline trailing-edge crack in Hastelloy B blade 14 after 14.25 hours (57 cycles) of operation. Etchant, aqua regia in glycerine. X250.

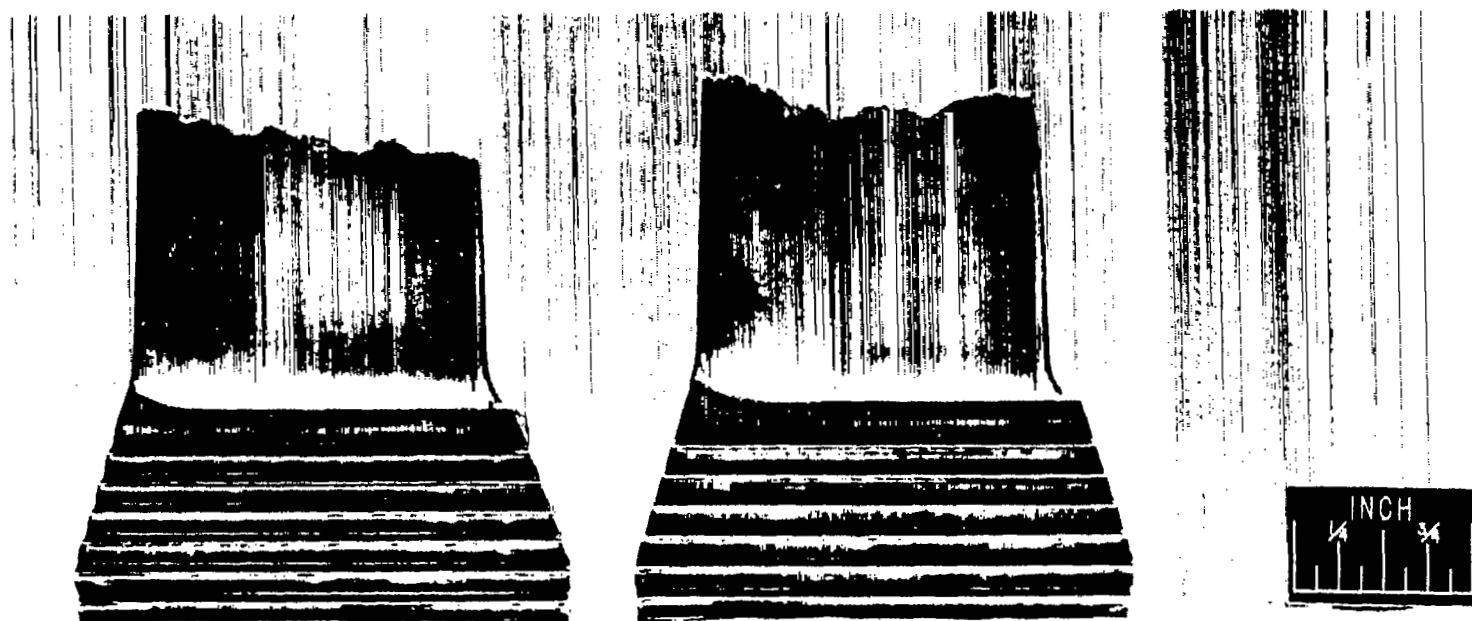


(a) Blade 25 fractured after 16.75 hours (67 cycles) of operation.

Figure 9. - Fractured Stellite 21 blades.



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(b) Blade 3 fractured after 28.75 hours (115 cycles)
of operation.

(c) Blade 1 fractured after 28.75 hours (115 cycles)
of operation.

Figure 9.-Concluded. Fractured Stellite 21 blades.

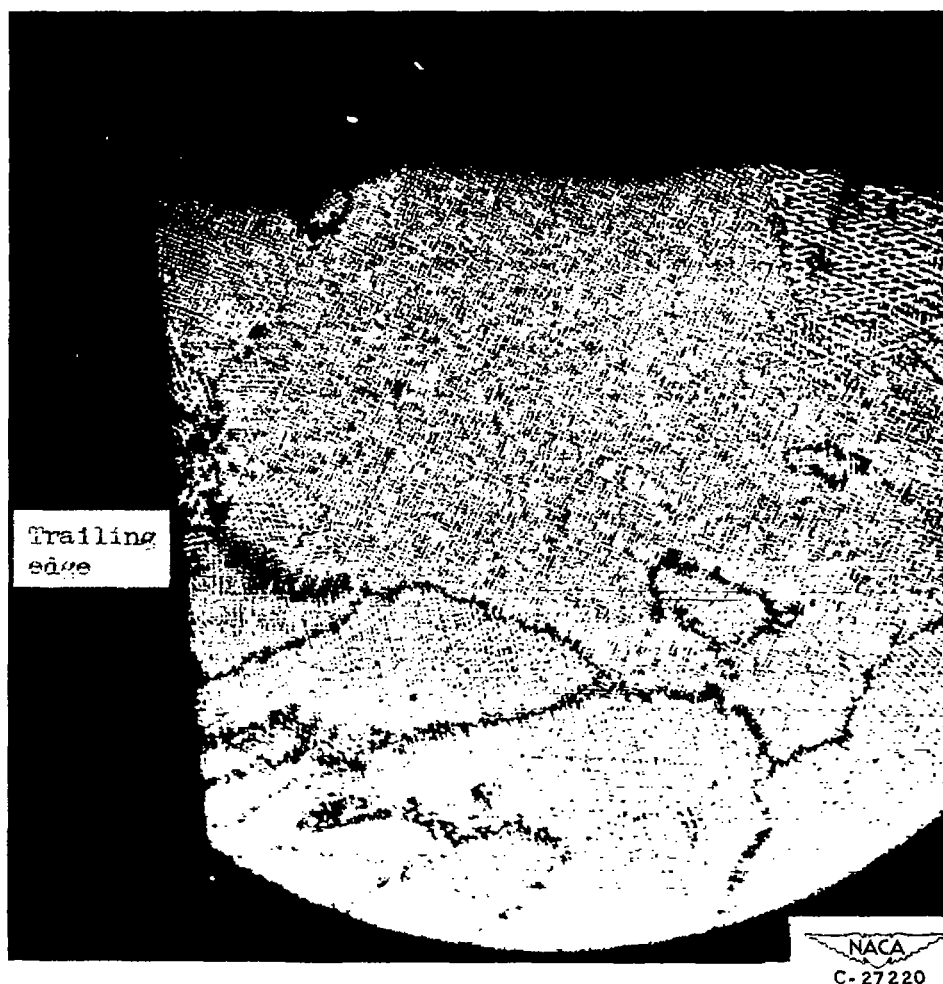
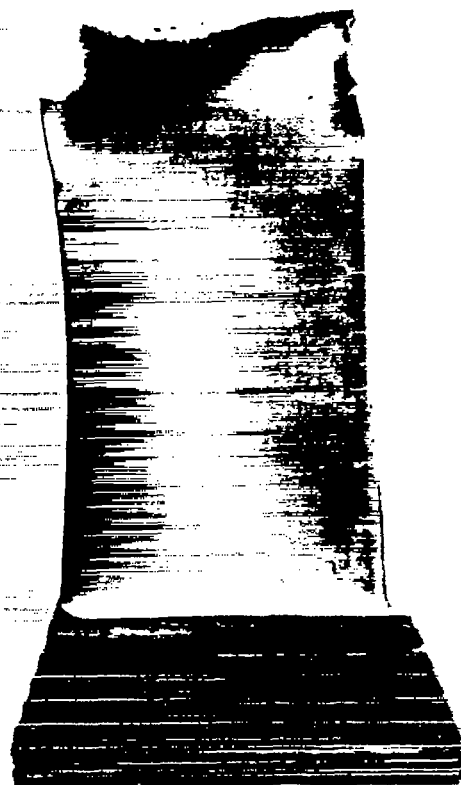


Figure 10. - Transcrystalline path in Stellite 21 fracture blade 25 after 16.75 hours (67 cycles) of operation. Electrolytically etched in 10 percent nitric acid and 10 percent ethylene glycol. X50.



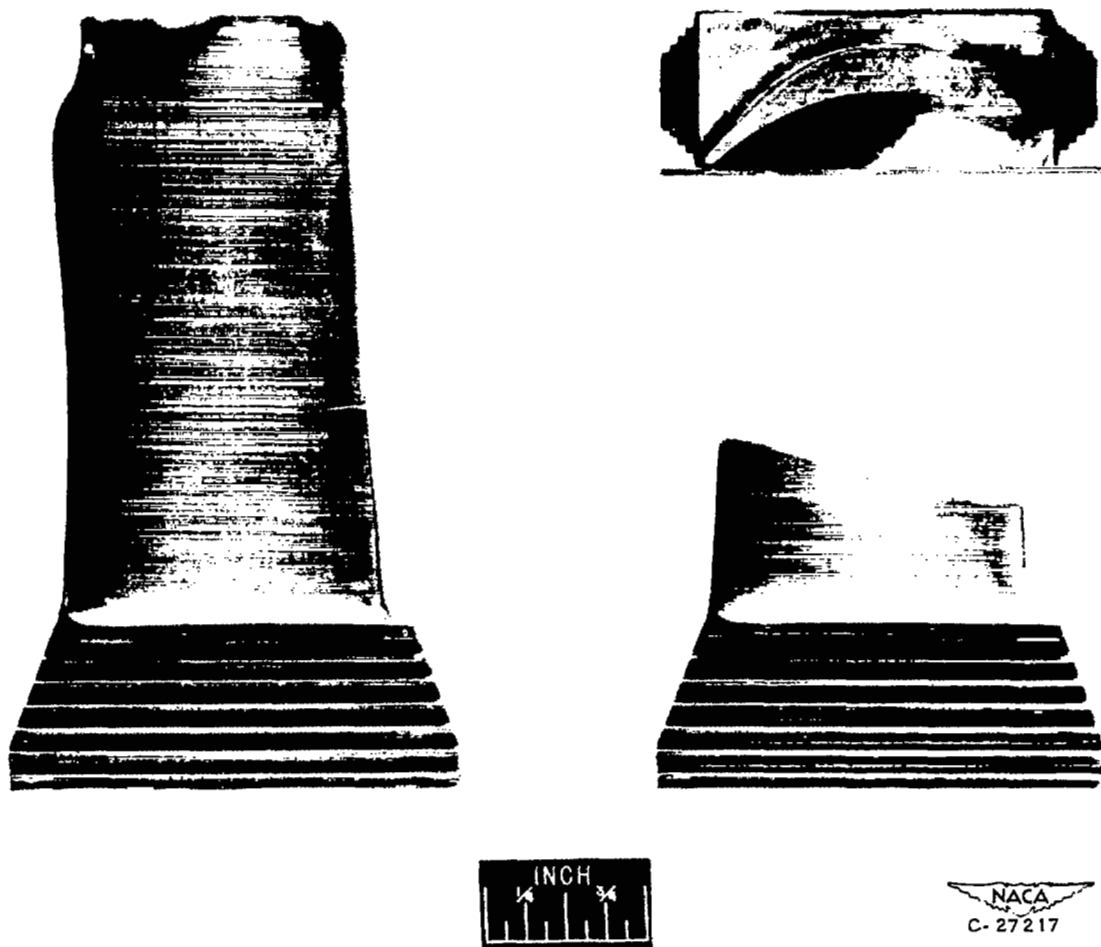
(a) Blade 52 after 28.75 hours (115 cycles) of operation.



(b) Blade 3 fractured after 28.75 hours (115 cycles) of operation.



(c) Fracture surface of blade 4 (fig. 11(b)). X2.



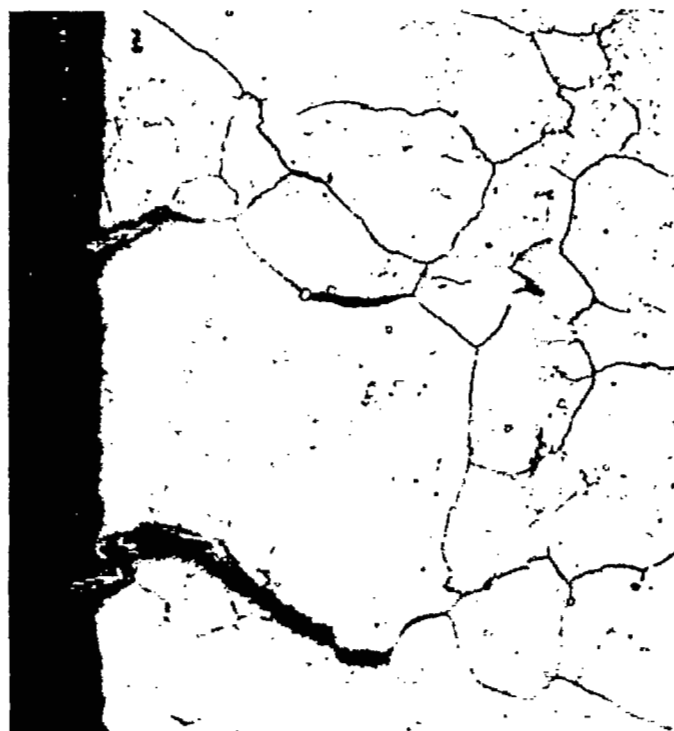
(d) Blade 34 after 18.47 hours (74 cycles)
of operation.

(e) Blade 54 fractured after 28.75 hours
(115 cycles) of operation.

Figure 11. - Concluded. Fractured and cracked Hastelloy B blades.



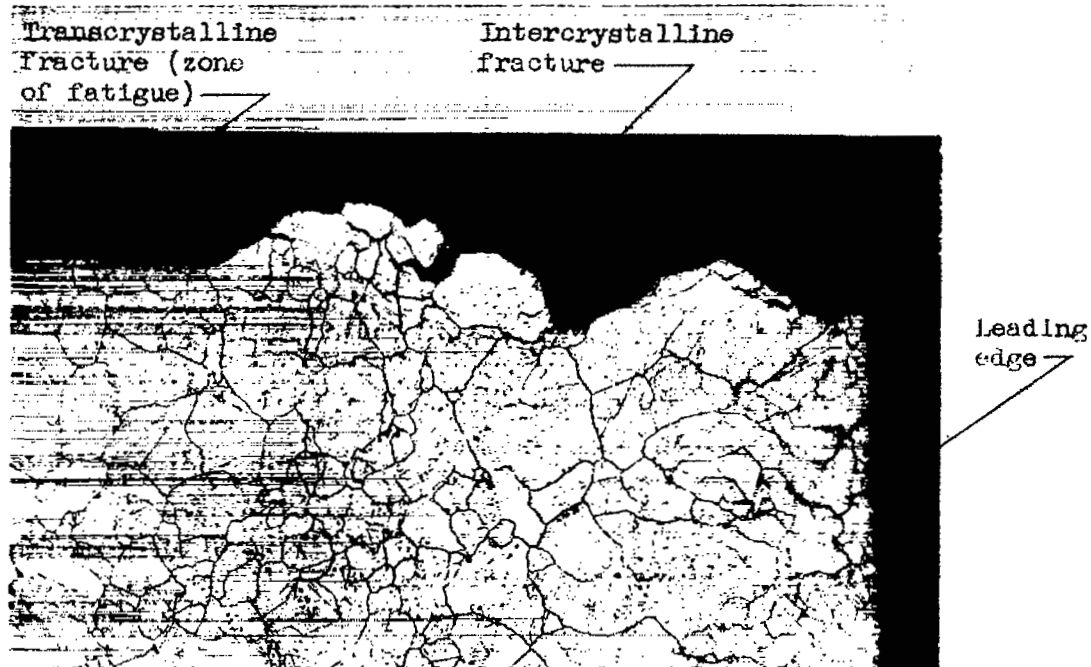
(a) X100.



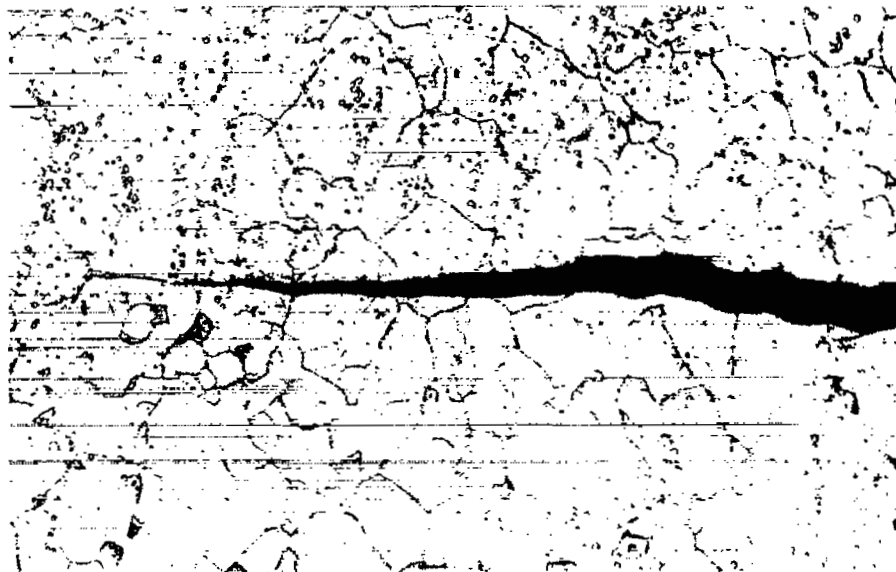
(b) X250.

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Figure 12. - Typical intercrystalline leading-edge cracks in Hastelloy B blades. Etchant, aqua regia in glycerine.



(a) Failure path from leading edge of fractured blade 4. X50.

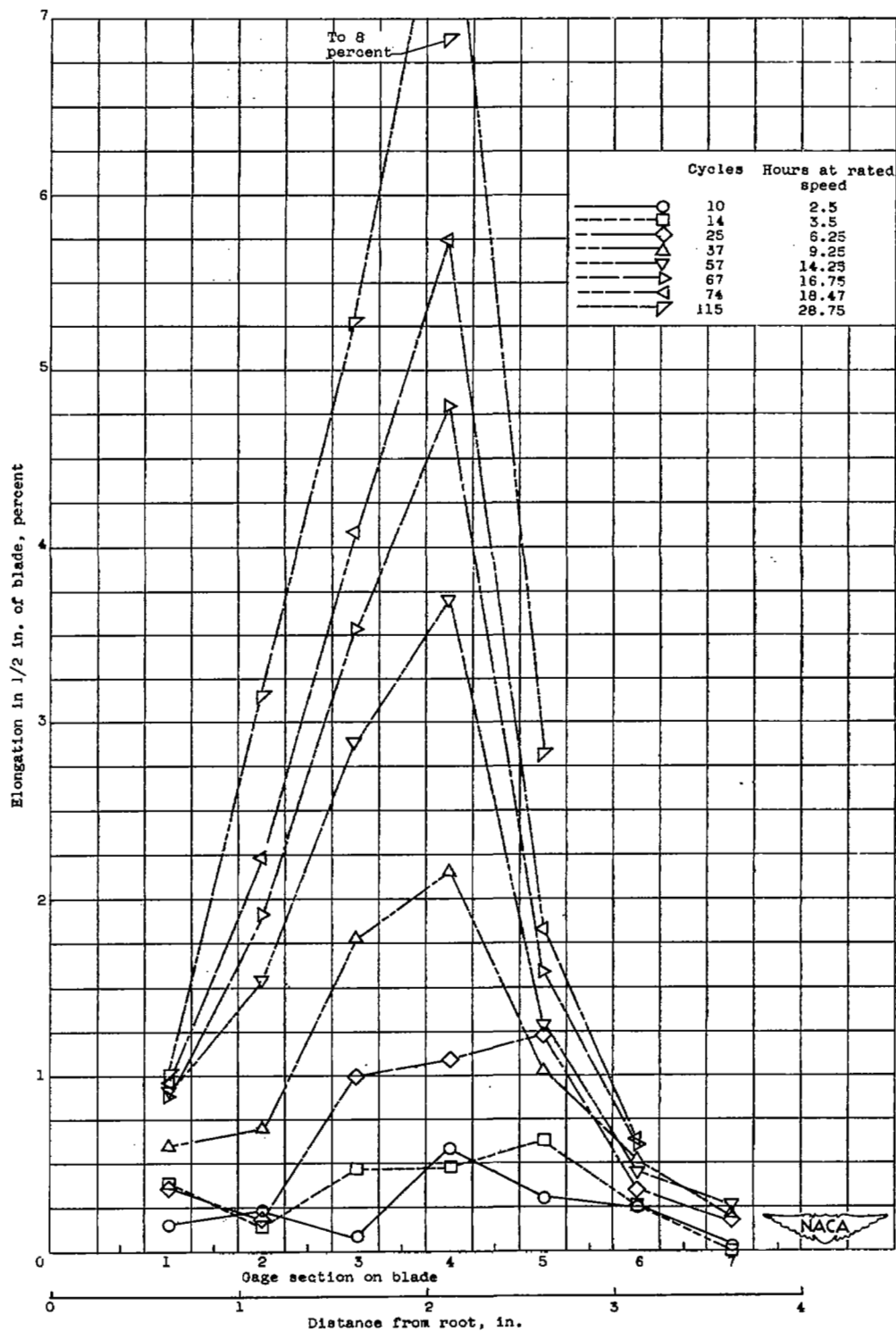


(b) Transcrystalline failure path in zone of fatigue of cracked blade 34. X100.

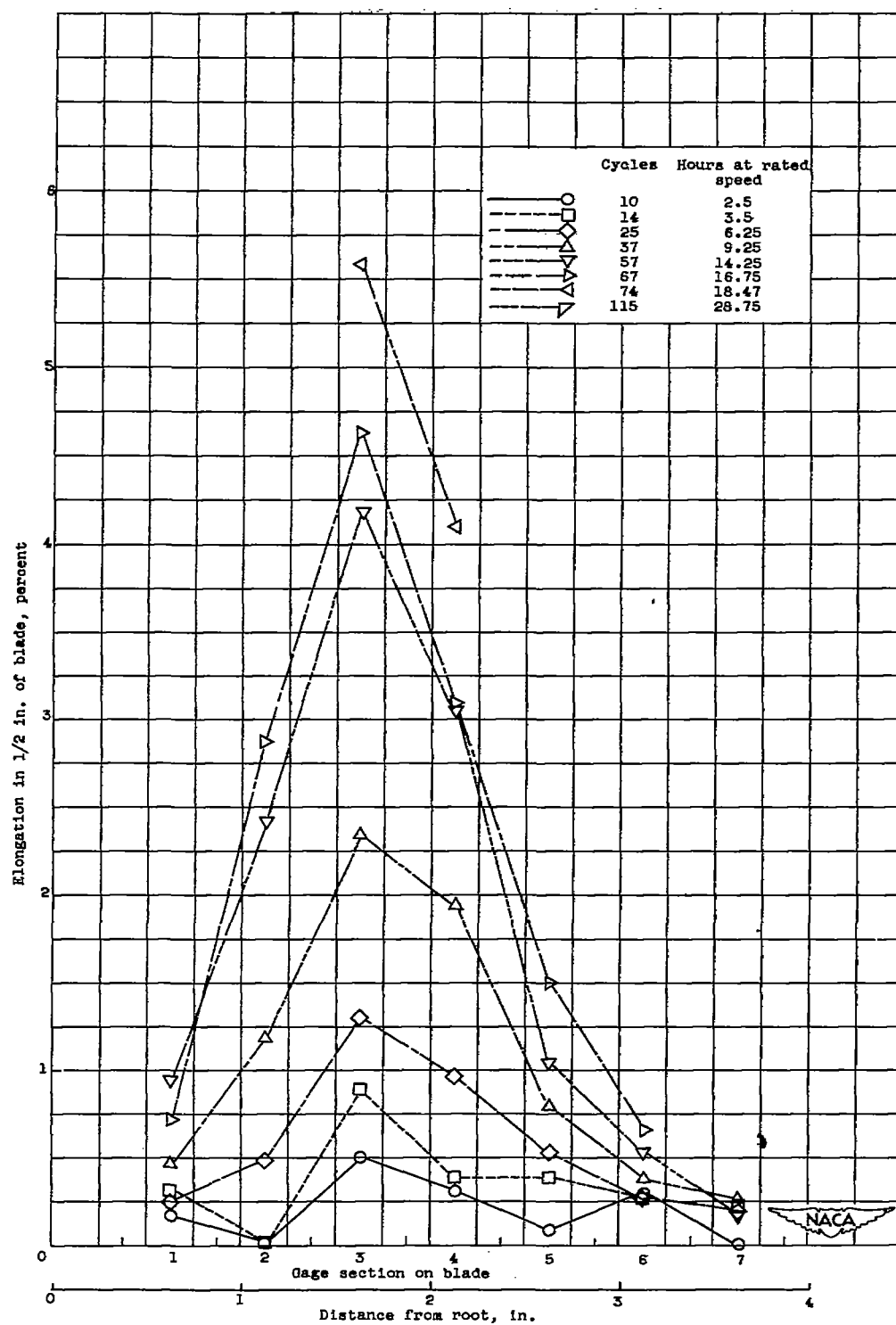
Figure 13.-Failure progression in Hastelloy B blades. Etchant, aqua regia in glycerine.



Figure 14. - Fractured blades at conclusion of operation.



(a) Hastelloy B blade 40.
Figure 15. - Elongation distributions along turbine blades.



(b) Hastelloy B blade 54.
Figure 15. - Continued. Elongation distributions along turbine blades.

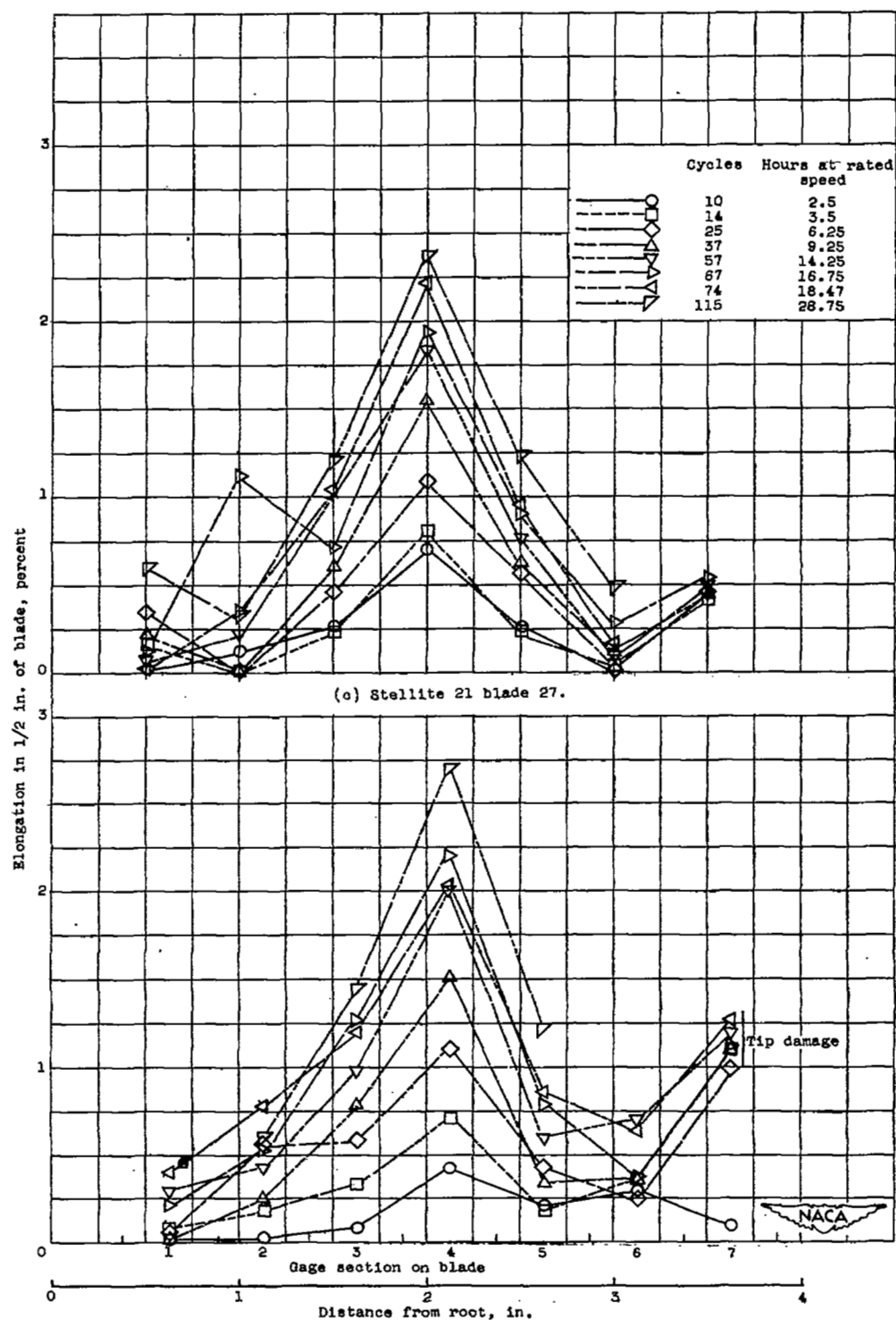
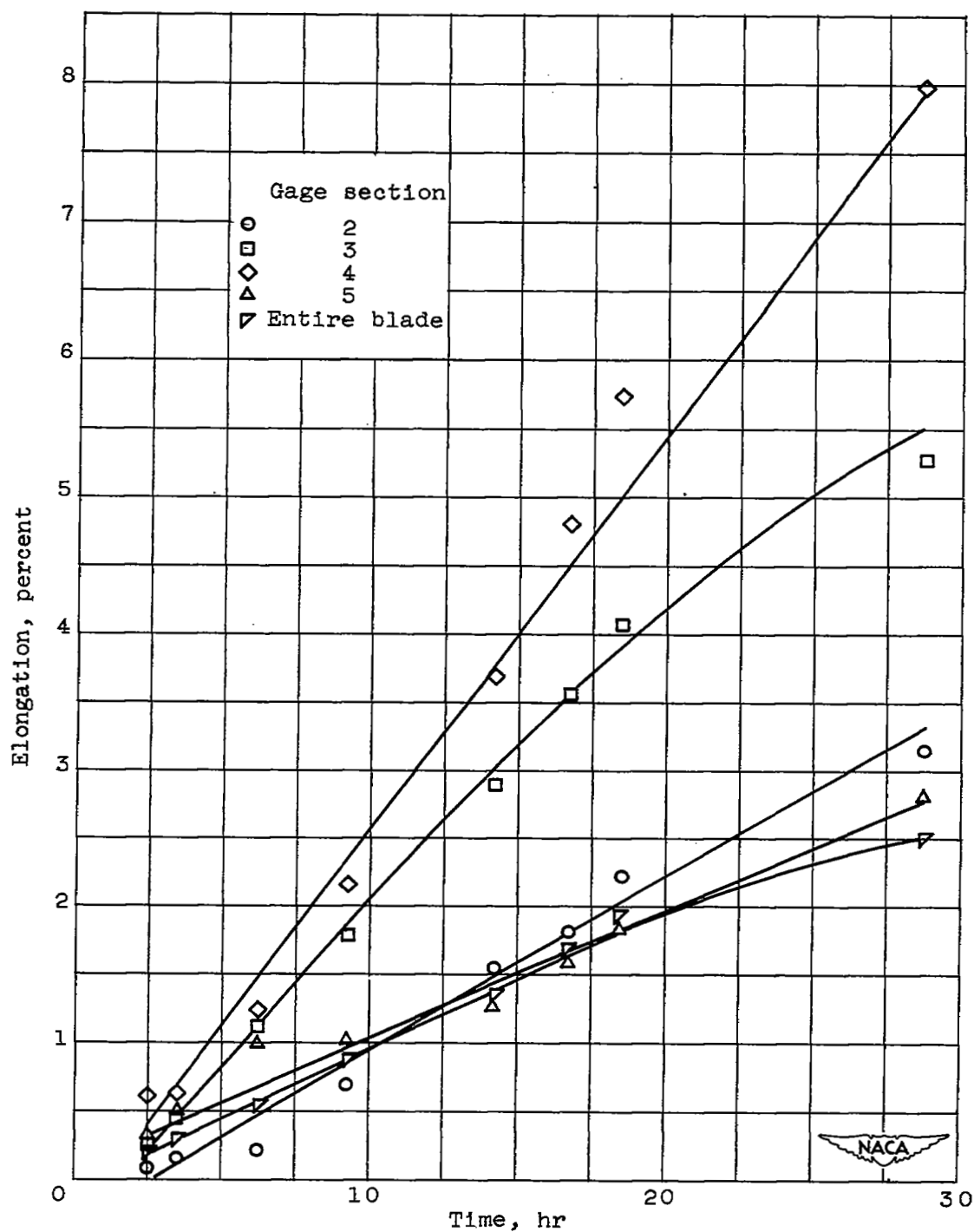


Figure 15. - Concluded. Elongation distributions along turbine blades.



(a) Hastelloy B blade 40.

Figure 16. - Blade elongation during turbine operation for those sections having greater than 1 percent elongation.

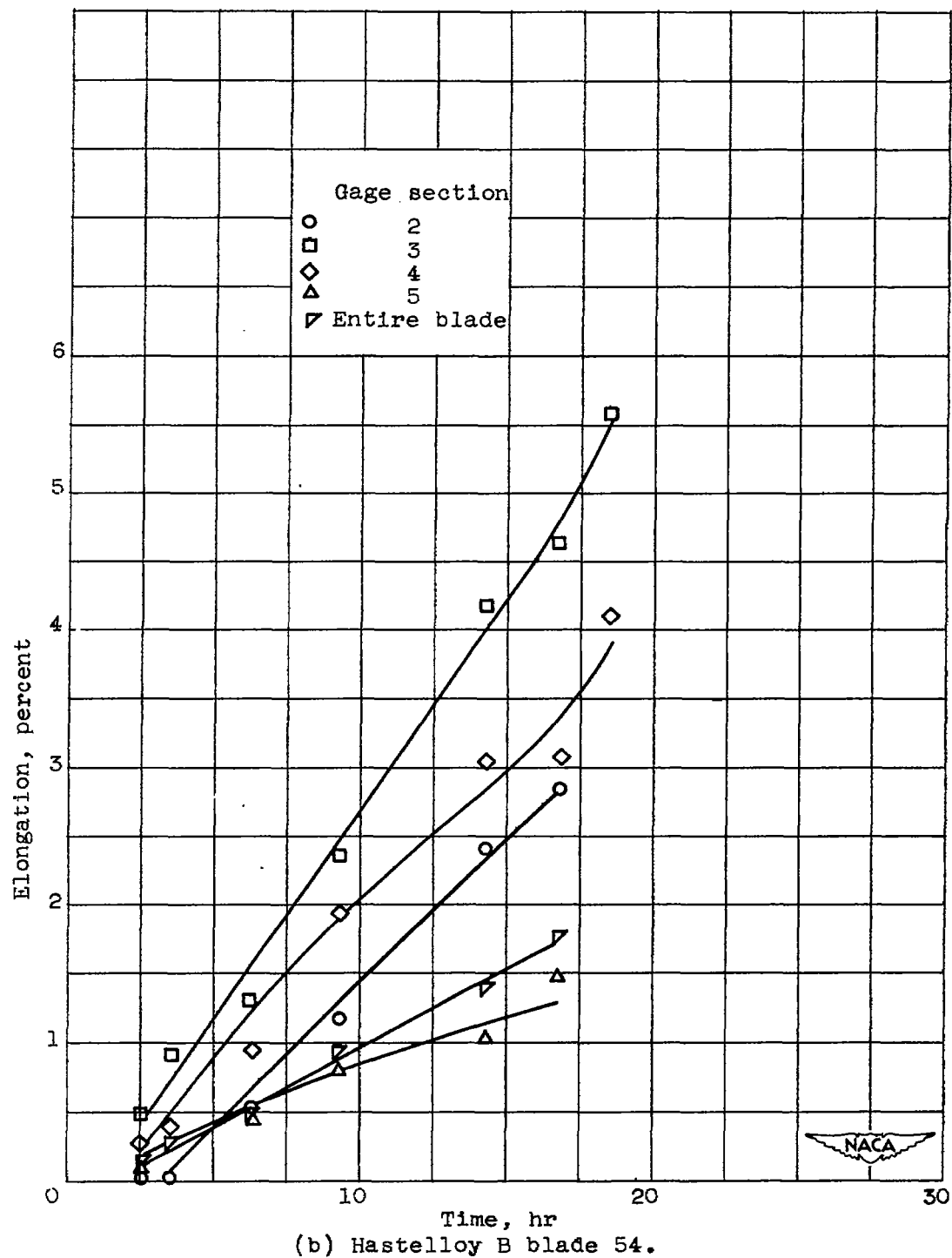


Figure 16. - Continued. Blade elongation during turbine operation for those sections having greater than 1 percent elongation.

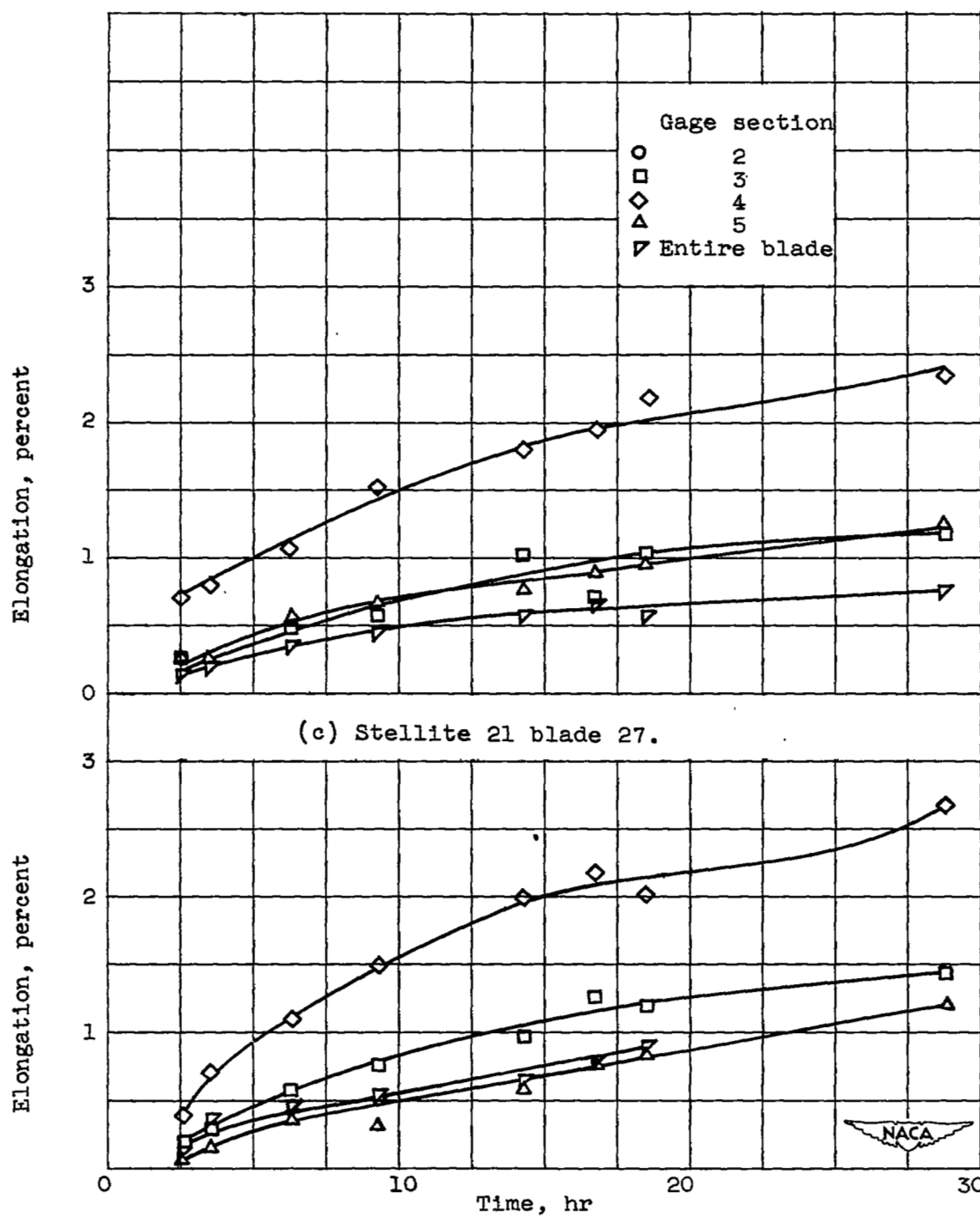


Figure 16. - Concluded. Blade elongation during turbine operation for those sections having greater than 1 percent elongation.

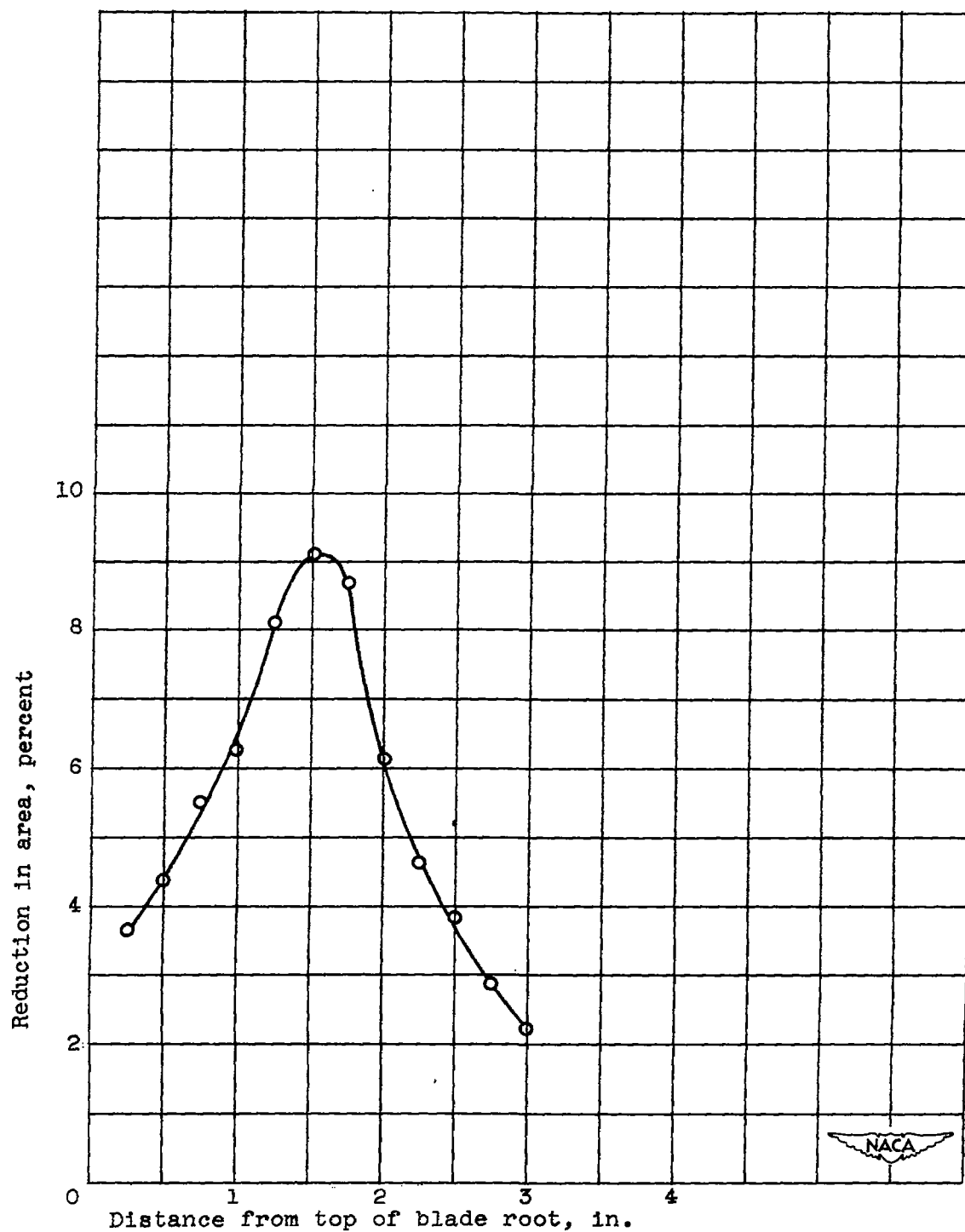


Figure 17. - Reduction in area in Hastelloy B blade after 28.75 hours (115 cycles) of operation.

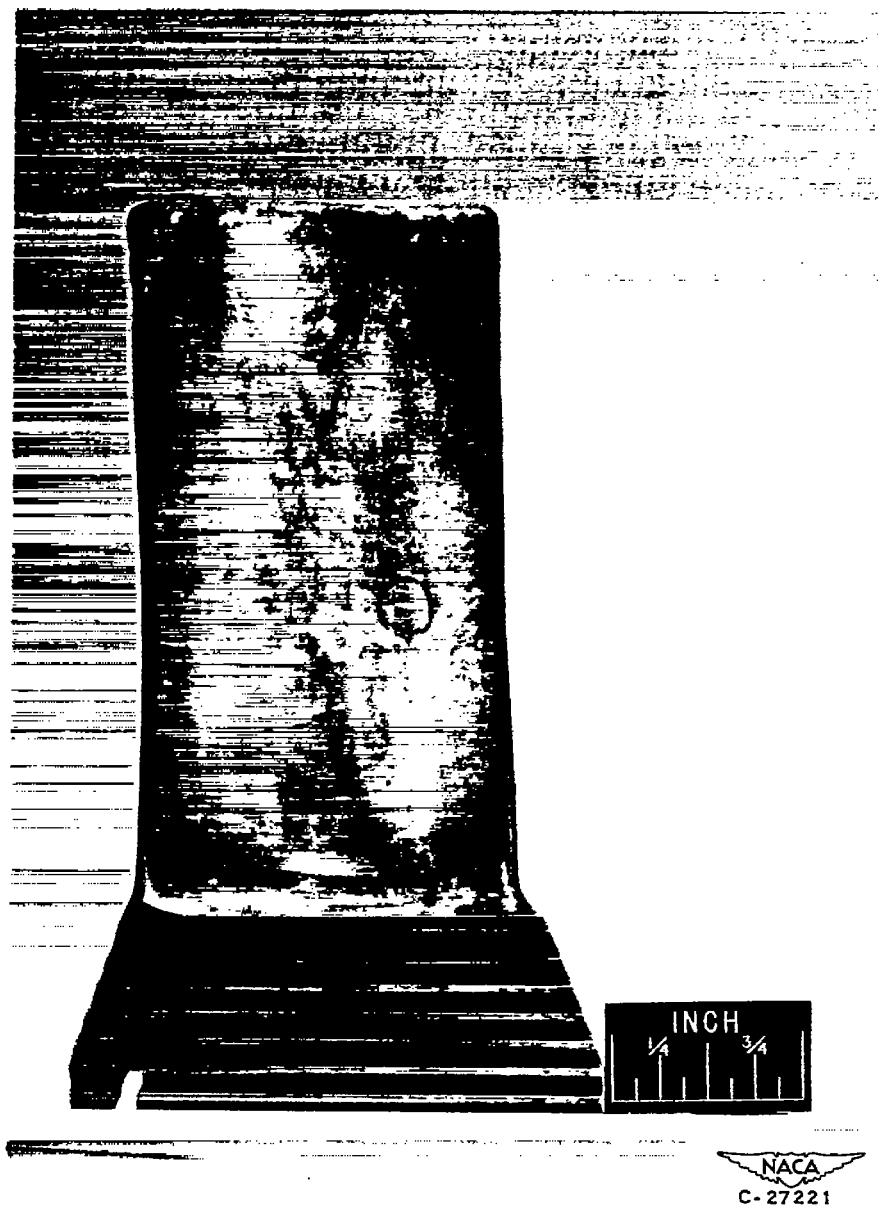


Figure 18. - Surface condition of Stellite 21 blade after 28.75 hours (115 cycles) of operation.

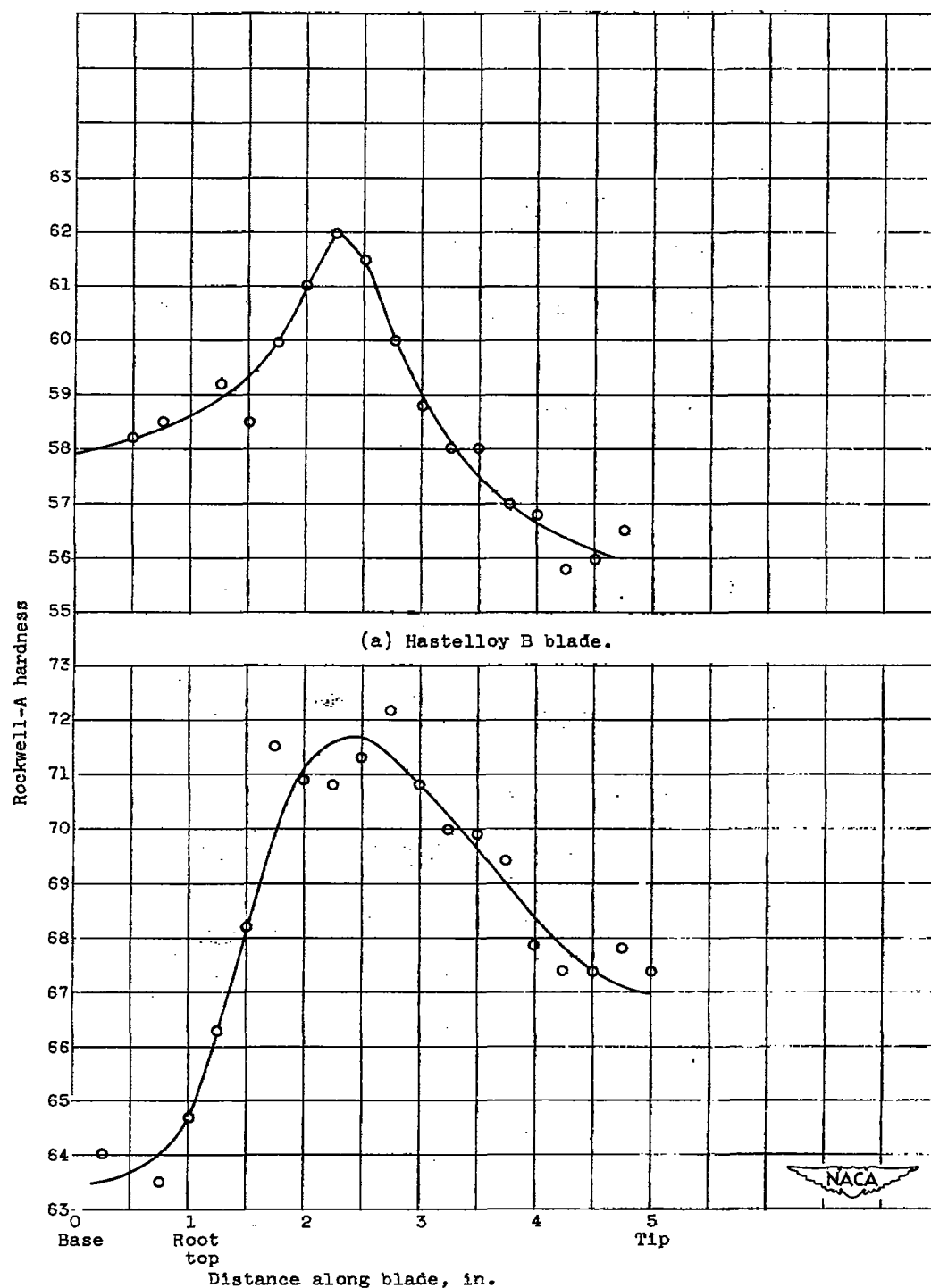


Figure 19. - Hardness distribution for blade after 28.75 hours (115 cycles) of operation.

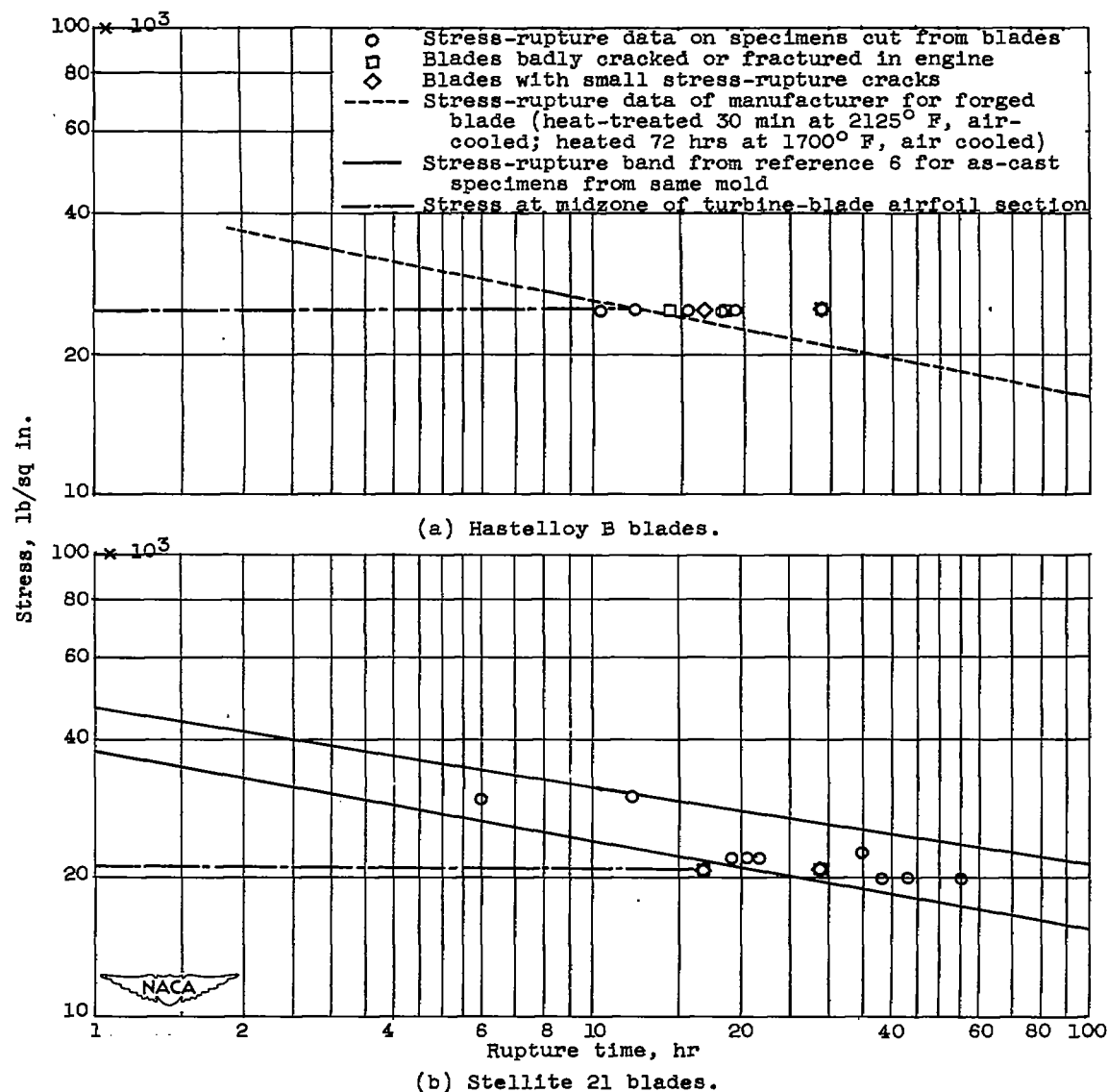


Figure 20. - Comparison of stress-rupture properties and engine blade life at temperature of 1500° F for alloys Hastelloy B and Stellite 21.

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